Pulse Power Supply System and Monitoring and Control System for Liquid Lithium Lens for Fermilab Antiproton Source

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Part A

Pulse Power Supply System

for

Liquid Lithium Lens for Fermilab Antiproton Source

CONTENTS

I.   Introduction.

For the test studies of the liquid lithium lens at BINP it is necessary to design and manufacture a pulse generator to provide such tests at a frequency of *2 Hz* with a load current of no less than *650 kA*. These tests are assumed to be done with the use of the pulse transformer produced at Budker INP for the test studies of lithium lens at CERN. This transformer is planned to be operated with the transformation coefficient *8:1*, thus the current pulse in its primary circuit, will be with an amplitude of no less than *81 kA*. Let us estimate the load parameters in terms of the transformer primary circuit. It is known that the FNAL lens inductance recalculated to the transformer primary circuit with the transformation coefficient *8:1* together with the transformer parasitic parameters is $2.45 \cdot 10^{-6} H$. Let us find out the load active resistance. The lithium rod of *2 cm* in diameter and *15 cm* in length at temperature *230 °C* ($\rho=45.2 \cdot 10^{-6} Ohm \cdot cm$) has an active resistance of $2.16 \cdot 10^{-4} Ohm$. The lens resistance reduced to the primary circuit of pulse transformer will be $1.38 \cdot 10^{-2} Ohm$. Let us take the worse case where an active resistance of the discharge contour is the same and then an active resistance of the contour will be of $2.76 \cdot 10^{-2} Ohm$. Thus the generator should be operated at an inductance load of $L=2.45 \cdot 10^{-6} H$ and an active resistance $R=2.76 \cdot 10^{-2} Ohm$. At the Budker INP, the experience collected sufficient for the construction of such generators. As an example of such a generator is that constructed for the tests of CERN lens enabled us to obtain current pulses of *1.5 MA* amplitude in the lithium lens of *4 cm* in diameter [1]. The brief description of the pulse generator produced by the standard scheme: capacitive storage–switch–load is given below. The charge device of the capacitive storage is given in more details. This is unconventional device: it was developed at BINP and to our opinion it fits ideally for charging capacitive storages operated in pulse generators at repetition rates ranging from a few fractions of *Hz* to several tens of *Hz*. Such a charge system was proposed by us for the TESLA collider (DESY, Hamburg) [2] and we want to present it now.

II.   General layout of the pulse generator.

Fig.1 shows a simplified schematic diagram of the pulse generator which enables one to obtain in the load the sine currents of *300 mks* duration with an amplitude of over *650 kA* at repetition rate of *2 Hz*. In this case, the capacitor banks C_1 and C_2 are charged by the charge device of constant power providing their charge of up to *7 kV* at the generator operating frequency of *2 Hz*. Exchange of poles is achieved through diodes D_3, D_4 and the load. Because of the low duty factor of the contour this circumstance does not affect practically the heat release in the lithium lens as seen from diagram in Fig.2 (power) but in this way, we remagnetize the saturation choke L_1 and the pulse transformer Tr_1. After test shots to the real load one can arrive at the final conclusion on whether an additional demagnetizing system from DC-source B_0 will be necessary or not. The generator discharge contour parameters are given below. Fig.2 shows values of current and voltage in the main points of generator calculated with CAD «NL-2.02» (designed by A. Smirnow). All the values are reduced to the primary winding of transformer Tr_1.

1. Load inductance .   *2.45·10⁻⁶ H*

2. Inductance of buses of capacitor banks   *0.3·10⁻⁶ H*

3. Total inductance of two thyristor modules   *0.3·10⁻⁶ H*

4. Inductance of choke L_1 in
   saturated state ($\int V dt = 4.5 \cdot 10^{-2}[v \cdot s]$)   *0.26·10⁻⁶ H*

5. Inductance of feeder line generator–load   *0.2·10⁻⁶ H*

6. Total inductance of charge contour   *3.51·10⁻⁶ H*

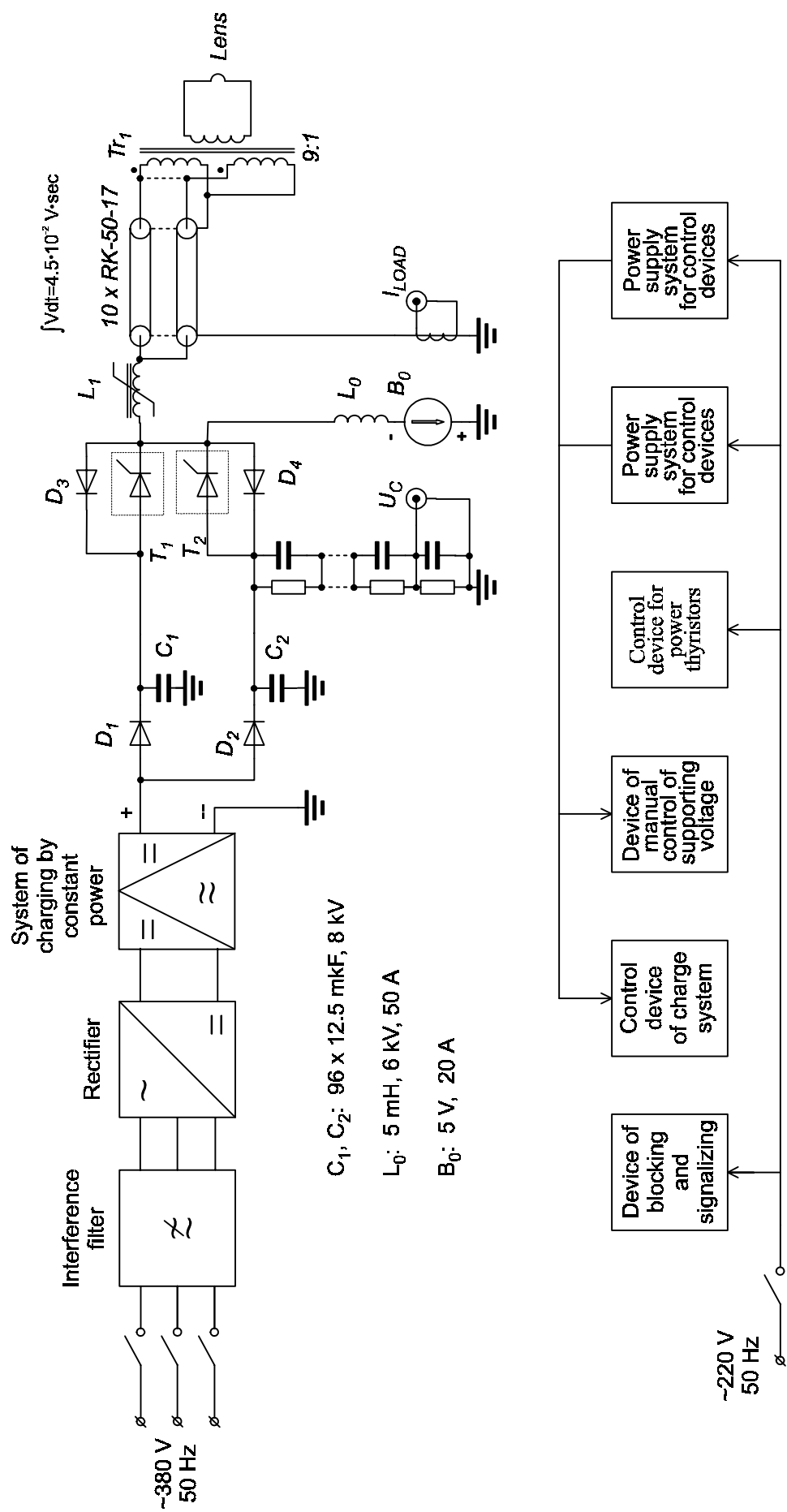7. Active resistance of charge contour   *< 3.5·10⁻² Ohm*

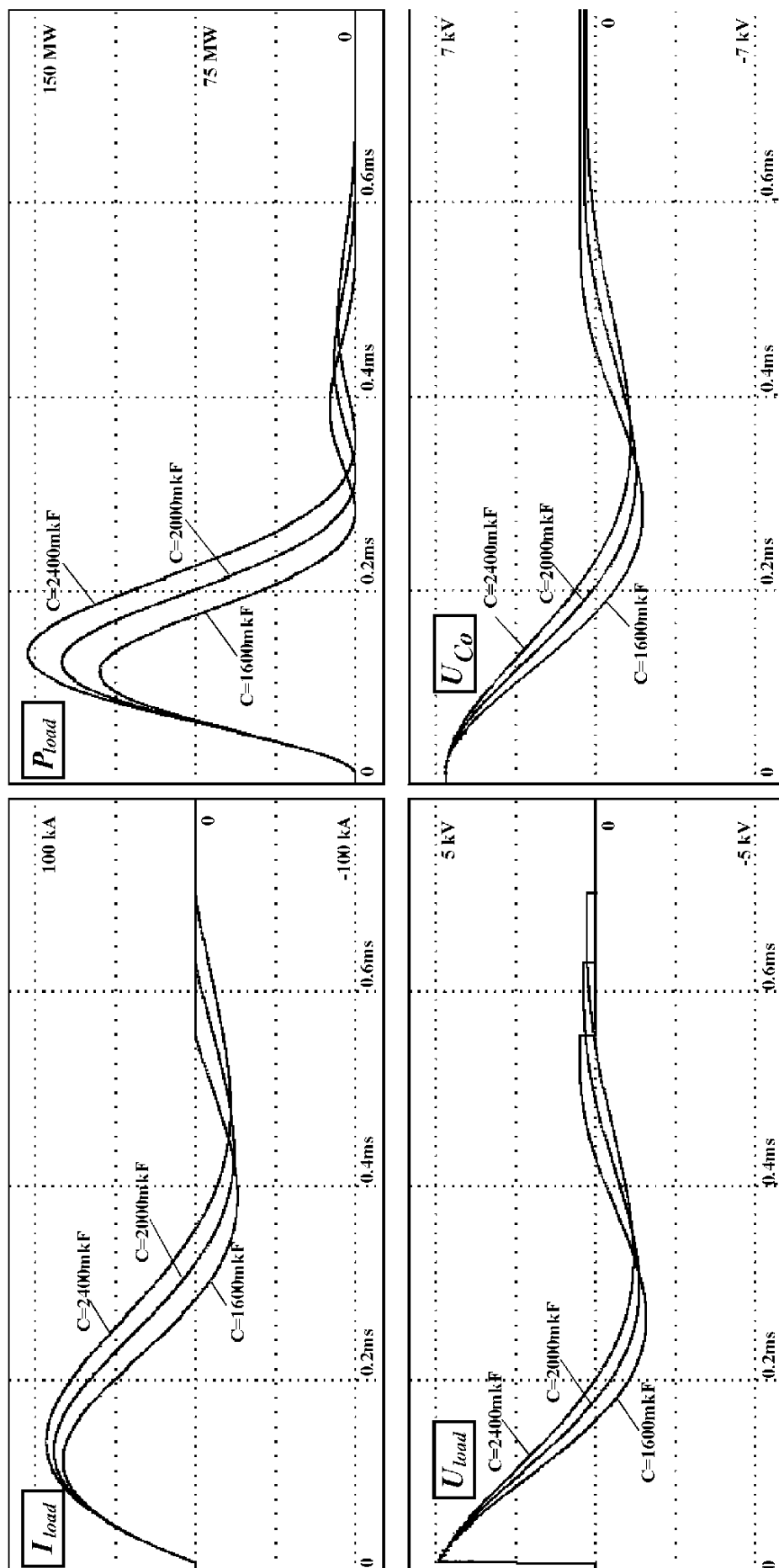Fig.1. Simplified circuit diagram of the pulse power supply system

Fig.2.Diagrams of current, power and voltages in the main points of pulse generator.

III.   Constant Power Charge Device

1. Conceptual design of a constant power charge device

General requirements to the charge device are mentioned as follows:

1. Maximum efficiency;
2. The mains should be loaded with a constant power with minimum ripple and phase distortions;
3. No breaks in the power consumption during the operation cycle of the modulator;
4. Smooth control of voltage at the capacitance in a wide range (from zero to the maximum value);
5. Turn on of the modulators with a smooth transition to the operation regime;
6. Stabilization of the charge voltage;
7. Variation of the repetition rate of the modulator operation cycles from fractions of a *Hz* up to tens of *Hz* while preserving the condition of constant power consumption from the mains;
8. Obtain a maximum power factor of the rectifier, feeding the charge device by both decreasing the harmonic composition of the consumed current and by the high value of *cos φ*;
9. Maximum correspondence for requirements harmonic control in electrical power systems;
10. Minimum rated power for elements of the charge device.

Proposed charge device, in the opinion of the author, in the maximum measure corresponds to all enumerated requirements.

The analysis of the used methods for charging the capacitors has shown that, as a rule, they can not meet to the full extent all the listed above requirements.

It is known [3] that the maximum efficiency of a charge circuit is provided by charging a capacitance with a constant value of current

$$\eta = \frac{1}{1 + 2k^2 \cdot \dfrac{RC}{T}},$$

where $k = I_{ef}/I_{av}$ is the charge current form coefficient, (I_{ef} is the effective current value, I_{av} is the average current), R is the active resistance in the charge circuit, C is the capacitance, T is the charge time.

In this context, the optimal system is the one providing the charge of the capacitance from a voltage source with a constant current. The charge of capacitance with a constant current, widely used in the world, is performed by means of a phase control over the mains pulses [4,5] or by means of a pulse–duration modulation of the source [6]. But the conclusion that the converter efficiency is maximal under a condition of a constant charge current is true only if the converter contains a single circuit. Electrical circuits of converters (from voltage sources to current sources) contain no less than two current circuits. When the charge current in the converter output circuit is constant, but the constant current from an input circuit source can not be provided, the condition of minimum relative energy loss can not be met.

A general calculation of the charge device efficiency is given in [3]. Main conclusions of this study are presented below. According to [3], a circuit of the charge device with an ideal converter without loss is given in Fig.3.

Fig.3. Circuit of charge device with ideal converter without loss.

The input circuit losses are accounted by a resistance R_1 and output circuit losses are accounted by a resistance R_2. The efficiency of the charge device η obviously equals to: $\eta = \eta_1\backslash\eta_2$, where η_1 is the input circuit efficiency, and η_2 is the output circuit efficiency. As a result the authors obtain the following equation:

$$\eta = \frac{0.5 + \sqrt{0.25 - k_1^2\left(1 + 2k_2^2 \cdot \dfrac{R_2 C}{T}\right) \cdot \dfrac{P}{P_k}}}{1 + 2k_2^2 \cdot \dfrac{R_2 C}{T}},$$

where k_1 and k_2 are coefficients of the current forms at the converter input and output (charge) circuits, P is the mean charge power on the capacitance C, P_k is the short-circuit power of the collider feeding system. (The effect of P_k on the choice of type of the charge device will be observed further).

Imagine the charge device, where the capacitance periodic charge is produced from a constant voltage source via an ideal voltage-current converter. The converter contains a device providing relative duration of charge current pulses, or a device for the phase control of mains pulses, and is used for keeping the time independent charge current. It is obvious that then the capacitance voltage and instantaneous power after the conversion will be linearly increased in time. As our converter does not contain a energy storage, comparable with the energy of the modulator capacitor, the instantaneous power at the converter input repeats the instantaneous power form after the converter. The conclusion is the following: the charge system with a time-constant current in the capacitor charge circuit, loads the power system from the saw law, when the power consumed (inside the charge interval) starts from zero and ends with a doubled value with respect to the mean charge power.

The input current form factor for this device is $k_1=1.16$, the efficiency of the charge device is decreased, but there exists a more important factor, which can make it impossible in principle to connect the device to the power system without special measures taken. This concerns the energy consumers whose mean power makes hundreds of MW.

An over two–fold "attack" on the power system with respect to the mean power caused by the DC charge will lead to a contradiction with the electro-technical standard for the electrical energy quality [7].

The value of the charge device efficiency and its optimal interaction with the power system is basically determined by a feasibility to transfer the energy to the converter at a

constant power [8] Such a system does not have the above shortcomings and has the following advantages:

1. A higher source utilization factor – this allows to decrease its mass;
2. Minimum possible losses in the converter input/output circuits;
3. Low-frequency "shocks" upon the power system (with lens repetition rate), hampering the operation of other consumers, are eliminated;
4. Meets criteria for charge devices, listed at the beginning of this chapter.

2. The choice of scheme of the power charge device.

BINP has successfully tested a charge system consuming a constant power of *300 kW* from the mains, which consists of three *100 kW* modules. The basic part of the module is a thyristor inverter converting the input voltage into current pulses at a high repetition rate, charging in portions the capacitor up to the required voltage through the step–up transformer. The module operation is described in more detail in [9]. Below in this paper will be also described the module operation in its application to our task. A sketch diagram of the device is given in Fig.4.
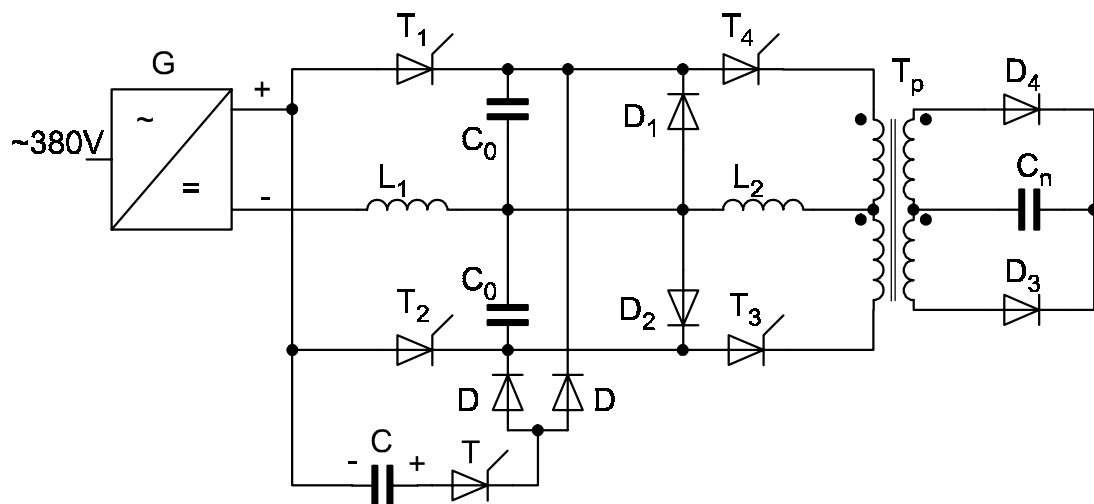

Fig.4. Simplified circuit diagram of a charge device with an electron protection.

The inverter consists of two loops. The first loop consist of a mains rectifier G, thyristors T_1 and T_2, a choke L_1 and dosing capacitors C_0, the second loop includes capacitors C_0, thyristors T_3 and T_4, diodes D_1 and D_4 and a storage capacitor C_n. The step-up transformer T_p used only to transform the inverter output voltage.

The inverter works in the following way. Capacitors C_0 are charged in succession from a low–voltage mains rectifier G up to its two-fold voltage by switching on thyristors T_1 and T_2 through the inductance L_1. Every half–period of the inverter operation they transfer their energy to the capacitor C_n, being discharged by switching thyristors T_3 and T_4 through the inductance L_2 to the primary winding of the transformer T_p. For a complete energy transfer from C_0 to C_n they are shunted by diodes D_1 and D_2. With the help of these diodes there is no over-charging of the capacitors C_0, the energy is completely transfered to capacitor C_n and there are provided initial conditions for the next charge cycle. The last process is the most principle one in the inverter operation. We have the situation, when the rectifier inside the charge interval works to dosing capacitors with zero initial conditions: $U_{Co}=0$.

But the capacitors C_0 are discharged completely with a full energy transfer to the storage capacitor C_n only to the value $U_{Cn} = U_G{\cdot}n$ ($U_G = 500\,V$ is the voltage at the rectifier, n is the transformation ratio of the transformer T_p). With a further increase in the voltage on C_n, the capacitors C_0 do not discharge completely, which leads to a reduction in the average value of the consumed current and a violation of the constant power consumption from the mains. The capacitor charging is finished at $U_{Cn} \approx (1.05 \div 1.1){\cdot}U_G{\cdot}n$, which is the maximum tolerable over-voltage in the circuit. Thus, the range $0 < U_{Cn} \leq U_G{\cdot}n$ is the condition for the optimal operation at a constant power consumption.

The control of the charge voltage level is performed by varying the pulse repetition rate of the inverter. The maximum repetition rate corresponds to the continuous inverter operation and the maximum charge voltage. The voltage decreases with the pulse repetition rate. The thyristors T_1, T_3 and T_2, T_4 are triggered by means of a functional "voltage-frequency" converter which is controlled with the help of a variable reference voltage. In case it is necessary to compensate parametric instabilities of the modulator elements, it is possible to compare the signals from the gauges with the reference voltage.

As is known from [8], the operation of a single charging device, provided the mean power consumed from the mains is constant, is characterized by ripples with drops to zero in the intervals between the charge pulses. At a maximum inverter repetition rate the phase shift

between the sine charge pulse of the current is equal to π. In this case, the efficiency coefficient $k_{ef} = I_{av}/I_{max}$ (I_{max} - maximum value of current) is equal to *0.637* and decreases with the increase in the phase shift during the voltage drop in the process of control. The multi phase design of the charge system decreases fluctuations (rippling) and makes the efficiency coefficient equal to $k_{ef} = 0.9$ in the two–phase variant for the phase shift by *π/2, 0.95* and *0.97* in the three – and four – phase variants, respectively. Hence, it capacitor charge device can operate consuming a constant power from the mains in a wide interval of voltage adjustment, or variation in pulse repetition rate of the modulator operation cycles. Such a mode of the liquid lithium lens operation is probably needed for adjustment, preventive maintenance and other work.

The problem of smoothly switching on the load into the mains (as well as its switching off) and of a slow growth (drop) of the consumed power is solved by applying the reference voltage to the functional "voltage – frequency" converter through a timer circuit.

The inverter does not require an insulating mains transformer in the rectifier *G*. Either one, or a number (*10 ÷ 20*) of inverters can operate from one high-current rectifier. Between the rectifier and the inverter an electron switch is used. It works together with emergency switches which are of a comparatively slow action.

The protection circuit (see Fig.4) operates as follows: the capacitor *C*, charged from the low power rectifier (*50 ÷ 100 W*) in the indicated polarity, is in a waiting mode. During the alarm situation, for example, when the operation fails or the inverter sticks, the rectifier current feeding the inverter goes out of the design mode. In this moment, when it reaches the determined level, the thyristor *T* is switched on by a comparator signal, and the reverse voltage from the capacitor *C* is applied to the inverter thyristors T_1 and T_2, at the same time the trigger pulses are taken off. The thyristor which was switched on at that moment (T_1 or T_2), switches off, the inverter alarm current is taken over by the circuit: the capacitor *C*, thyristor *T*, and one of diodes *D*. After the polarity reversal of the capacitor *C*, the thyristor *T* is switched off, and the protection circuit is restored.

Note one more feature of the proposed charge device - it is powered from a non-controlled diode rectifier. As discussed above, many of charge devices [4,5] (the charge system from Fermilab is among them [10]) are based on thyristor rectifiers, where the capacitor charge mode is preset by a thyristor switch phase. As a rule, the thyristor switch phase is close to π at the beginning of the charge interval, and as the capacitor is being

charged, it decreases, approaching at best the value of the mains phase, i.e. $\pi/3$. This fact impairs the harmonic composition of the consumed current and leads to a change of $\cos \varphi$ (shift of voltage and current vectors) inside the charge interval. The conclusion is that for a charging device based on rectifiers with thyristor regulators:

- there is no compensating odd harmonics, because the relationship between their amplitudes constantly varies;
- there is no completely compensating $\cos \varphi$.

The charge systems with thyristor regulators reduces the rectifier power factor. It is known [11] that the rectifier power factor χ depends on the shift factor $\cos \varphi$ as well as on the distortion factor ν:

$$\chi = \nu \cdot \cos \varphi.$$

Both the factors ν and $\cos \varphi$ are notably reduced when coming to a deep regulation - this is a significant disadvantage of the charge systems based at the rectifiers regulated with a help of a line voltage angle α.

An our constant power charge device for capacitors operate from a non-controlled diode rectifier.

Note some disadvantages of the charge system described:

1. the charge device is based on the inverter, that is, as a powerful frequency converter, a source of radio interference voltage. That is why it is necessary to connect an interference filter at its input. The industry produces a great number of interference filters for different currents and voltages with a working damping of *60, 80* and *100 dB*;
2. the inverter is a source of noises of the sound range; the main sources of noise are the chokes L_1 and L_2, and transformer T_p. We partially decrease this disadvantage placing these elements in a tank filled with transformer oil.

In conclusion note, that it is no good using serial inverters produced by different manufacturers for industrial purposes in the charging device. This inverters can not provide the constant power consumption mode, as these are one-circuit systems (they are based on a

IGBT transistor or thyristor bridge). The device suggested here has two circuits, and the circuit connected to the mains operates so, that while transmitting the energy to the modulator capacitance, the dosing capacitors C_0 discharge to zero inside the charge interval at each cycle of the inverter operation, and their initial conditions are not changed.

3. Choice of the inverter operation frequency

The operation frequency of the inverter was chosen taking into account most uncostly electronics and electro-technical components, the optimization of the inverter elements by the mass – size parameters, and the method of the voltage stabilization on the capacitance.

The maximum frequency of the inverter operation is determined by the characteristics of the thyristors used, in particular by the time of their switch off. The analysis made at BINP shows that at acceptable energy parameters of the choke L_2, to be optimized by its mass minimum and the efficient value of the current transmitted to the capacitance, the switch off time t_{off} may make $10 \div 15\,\%$ of the duration of the charge current half - sinusoid. The industry produces comparatively cheap inverter thyristors with a switch off time of $10 \div 15\,\mu s$. Thus, the availability of parts makes it possible to choose the duration of the inverter frequency half – period up to $100\,\mu s$. The upper limit for the frequency may be defined by the choice of the ferromagnetic for electro-technical components of the inverter. The main factor will be the idea to use inexpensive electrical cold - rolled steel. These steels up to frequencies of $3\,kHz$ are beyond competition compared to Permalloy. We have chosed the frequency value $2.5\,kHz$. Fig.6 shows the current and voltage diagrams on basic components of inverter. The charge device efficiency is 0.93.
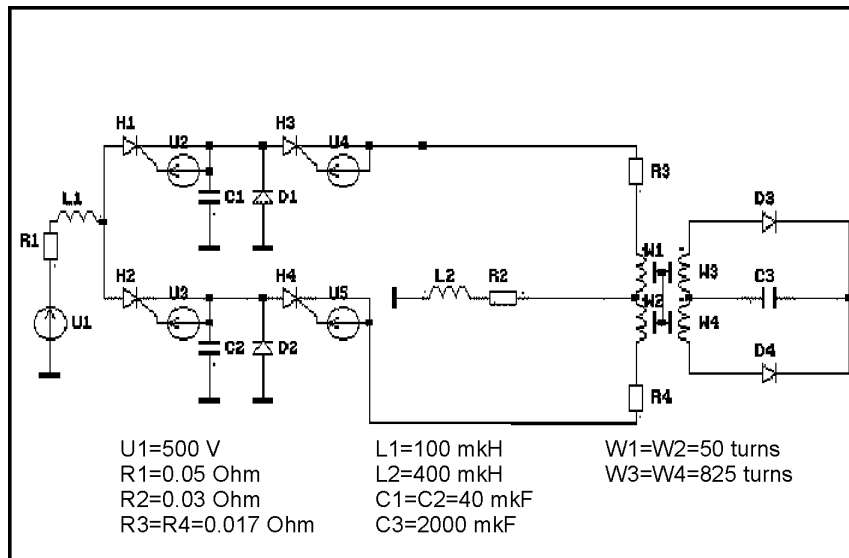
U1=500 V   L1=100 mkH   W1=W2=50 turns
R1=0.05 Ohm   L2=400 mkH   W3=W4=825 turns
R2=0.03 Ohm   C1=C2=40 mkF
R3=R4=0.017 Ohm   C3=2000 mkF

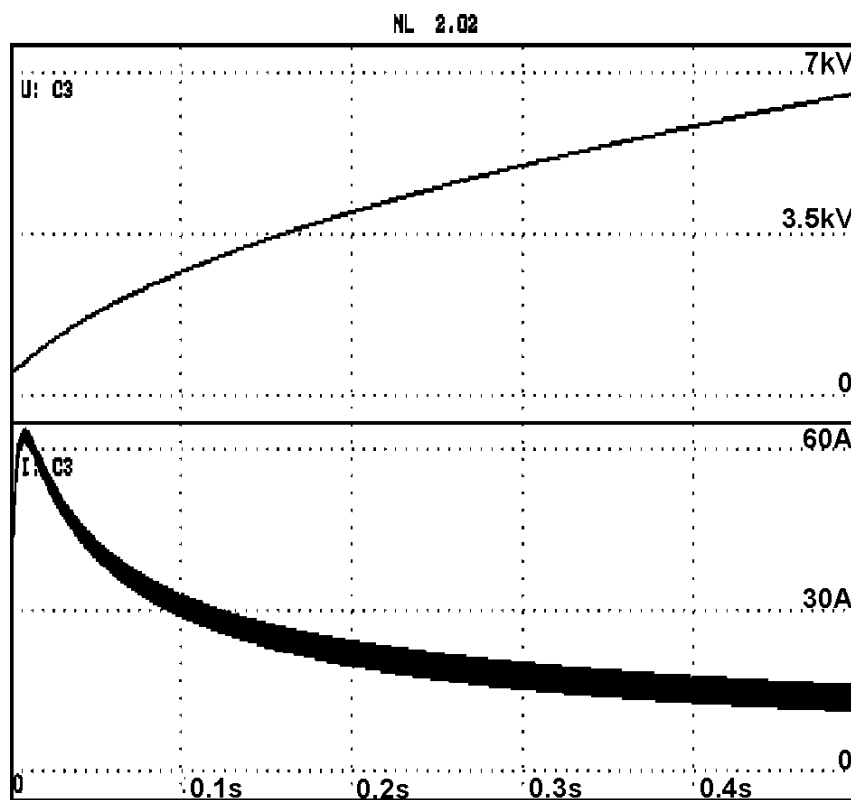**Fig.5a. Scheme of the charge device for calculations.**

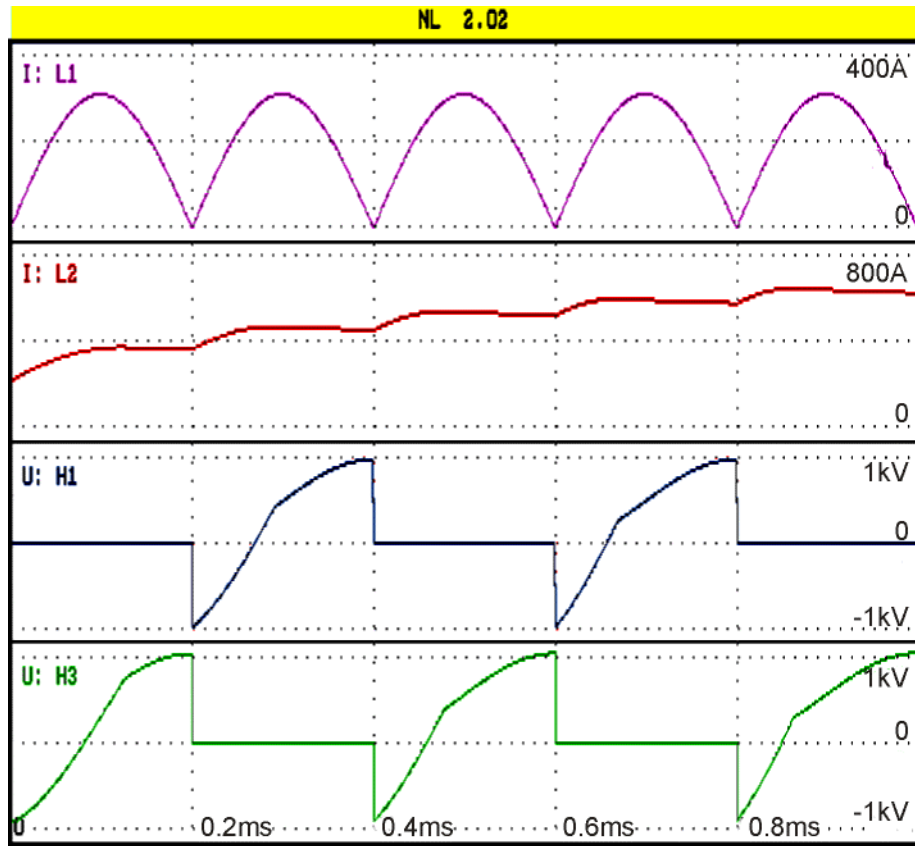**Fig.5b. Diagrams of charging current of the modulator storage capacitor and voltage on it.**

Fig.6a. Diagrams of currents through chokes *L₁* and *L₂* and voltages on inverter thyristors *H₁* and *H₃* at beginning of charging.
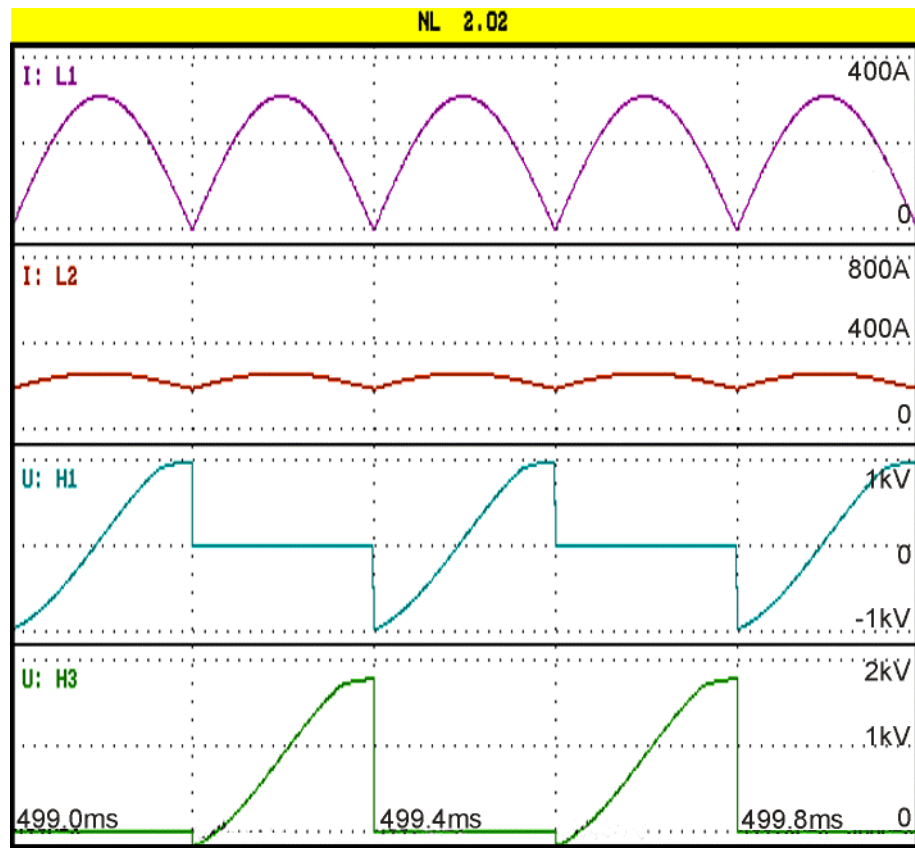
Fig.6b. Diagrams of currents through chokes *L₁* and *L₂* and voltages on inverter thyristors *H₁* and *H₃* at end of charging.

IV. Thyristor commutator.

The energy commutation from the capacitive storage to the load is performed by two thyristor modules one of which is shown in Fig.8. The module consists of 20 thyristors T253-800-24 with 5 simmetrically located thyristor branches with 4 thyristors *1* connected in series each (Fig.8) Thyristors in a branch are pressed in axial direction via yoke *10* by bolts *2* with a force of *2.3 t*. For the branch insulation it is used the insulator *3* designed for an appropriate force and for the compensation of forces at thermal changes the washers of plate kind *9* calibrated by the total force are envisioned. The basic support component of the structure is the power rod *4* designed at a total force of no less than *5x2.3 t* being the air conduit at the same time. The air is applied through the pipe *5* passes into the inner cavity of the power rod *4* and plate radiators *6* are air cooled through the hole in the rod. In the upper part of the module there five reactive coils *7* each to be connected in series to one of the thyristor branches. The necessity of introducing the parasitic component into the module structure is dictated by the necessity of equalizing currents between parallel branches; the inductance of one coil is *$2.6 \cdot 10^{-6}$ H* so, the total parasitic effect for 10 coils is *$2.6 \cdot 10^{-7}$ H*. The module is connected to the generator circuit by collector buses *8* to one of which the lower part of commutator is connected by isolated pipes. Each thyristor of the module is triggered from separate pulse ferrite transformer through yoke of which the primary winding wire passes whose isolation is designed for the total voltage. The dynamic and static division of voltage between thyristors connected in series is conventional; it is placed on boards around module and it is not shown in Fig.8. The total weight of one module is about *50 kg*. Basic characteristic parameters of thyristors are given below.

1. Repetition peak off-state voltage U_{DRM} *2400 V*

2. Repetition peak reverse voltage U_{RRM} *2400 V*

3. Mean on-state current I_{TAV} *800 A*

4. RMS on-state current I_{TRMS} *1850 A*

5. Surge on-state current (τ=*1 msec* U_{RRM}=*0*) I_{TSM} *32000 A*

6. Critical rate of rise of on-state current $(di_T/dt)_{crit}$ *100 A/mks*

7. Turn-on time t_{dt} *30 mks*

8. Turn-off time t_g *500 mks*

9. Mounting force F *22000 N*

The thyristor parameters provide the hope for that two modules enable the commutation of current pulses of sine shape of an amplitude no less than *100 kA*.

V.   Saturating choke.

In the pulse generator under construction the thyristor commutator should be designed for the current growth rate $\frac{di}{dt} \geq 1000\,A/mk\sec$. Ten parallel branches of thyristor commutator enable the operation with such of current growth rate however for higher reliability of the generator we use the conventional way of reducing the current derivative at energizing thyristors – we introduce the saturating choke connected in series to the discharge contour shown in Fig.9. Its design is determined by the purpose to obtain the maximum duty factor, minimum inductance in saturated state and by the possibility to achieve the required time delay of current pulse. On the flat core made of electrotechnical steel Э3425 with a band thickness of *0.08 mm* two wide copper buses are placed forming two turns. These turns are connected in parallel, the copper thickness exeeds the operating skin layer thus providing the maximum duty factor of the choke. The choke measured inductance in its saturated state is *0.26·10⁻⁶ H*.

VI.   Matching pulse transformer.

The test of lithium lens is planned to be performed with use of available at BINP transformer (Fig.10a,b,c) previously produced for the tests of the CERN lithium lens. It was operated over one million cycles with a current of *1 MA* on lens with an inductance *L=4·10⁻⁸ H* at pulse operation *~1.5 mks* and pulse energy of up to *100 kJ*. In the development of the transformer we focussed mainly on providing its reliable operation at large current amplitudes under conditions of high level radiation of antiproton target stations and lowering its parasitic parameters.

The transformer is a thick wall tore of rectangular cross section with an outer diameter of *420 mm* being a secondary turn with a cut on its inner diameter for the lens connection. Inside the tore there is circular magnetoguide of rectangular cross section separated on its inner diameter from the secondary turn by the insulation air gap. The basis of design scheme of the transformer is the principle of equilibrium primary winding each coil of which is placed in the holes in thick walls of the secondary coil with symmeric gaps and it does not interacts with neighouring coils. In such a design the scattering inductance of the secondary winding is equal to zero and the scattering inductance of the primary winding is proportional to the number of its coils and it depends on insulation gaps. Each of 18 primary turns of the transformer (we recommutate the primary winding to two windings connected in parallel by 8 turns) is formed by sections of coaxial lines of rods passing in axial direction through cylidrical holes in the body of the secondary coil by one in the inner diameter and by two in the outer diameter. The rods are connected in radial direction by flat wedge jumpers located in radial grooves on the ends of the secondary turn. The transformer ends are covered by ring copper caps so that over the plane of wedge jumpers there are similar *3 mm* gaps thus providing equal magnetic fields on their surfaces and equilibrium of the winding.

The connection of cylidrical pars of winding by flat jumpers is made by collet clamps. Each jamper is supported by ceramic insulator inserted into cylidrical bores in the bottom of groves in the body of the secondary turn. The massive secondary turn of the transformer is water cooled and the primary winding turns are cooled by air fanned through insulation gaps in axial direction. The temperature of primary winding can reach *100°C* determining the pulse repetition rate. Such a transformer with iron cross section of *180 cm²* provided a current over *1 MA* at pulse duration of *3 ms*.

VII.   Capacitor bank.

The total capacity of the capacitor bank of the pulse generator should be *2400 mkF*. In order to reduce the hazard of breakdown for thyristor commutators if one of them does not work the bank is divided into two sections and one section is commutated by one thyristor module and the second – by another module. The basic parameters of the capacitor bank is given below:.

1. Capacity of one capacitor   *12.5 mkF*
2. Capacitor test voltage   *8 kV*
3. Number of capacitors in a bank   *192*
4. Indactance of a capacitor $4 \cdot 10^{-7}$ *H*
5. Inductance of additional coil 10^{-5} *H*
6. Total inductance of capacitor bank with buses $0.25 \cdot 10^{-6}$ *H*
7. Total capacitance $2.4 \cdot 10^{-3}$ *F*

In order to avoid the explosion of one of capacitors at its break down an additional inductance of *10 mkH* is connected in series to each capacitor. Thus, the short circuit current will be limited to the required value.

VIII. Pulse generator testings

At this time the pulse generator by the scheme in Fig.1 have been assembled. The capacitor battery of generator consists of two sections of $1.2 \cdot 10^{-3}$ F capacity, so the total capacity of the battery is $2.4 \cdot 10^{-3}$ F and its testing voltage is $8\,kV$. Such battery will allow to carry out the lens testings at a voltage up to $6\,kV$ and $2\text{-}3\,Hz$ frequency. For the experimental turnings on a special dummy lens with electrical parameters close to the proposed lens ones was manufactured. During the testings the current in lens was rised up to $760\,kA$; the voltage of capacitor battery was about $5\,kV$. Oscillogram of current is shown in Fig.7.

Testings were made at $0.5\,Hz$ frequency. The frequency gain was limited by the heat removal possibility from the dummy lens. These testings have shown/proved the normal operation of the pulse generator and possibility to carry out all experiments of the liquid lithium lens with it. Fragments of pulsed generator are shown on Fig.11a,b,c.
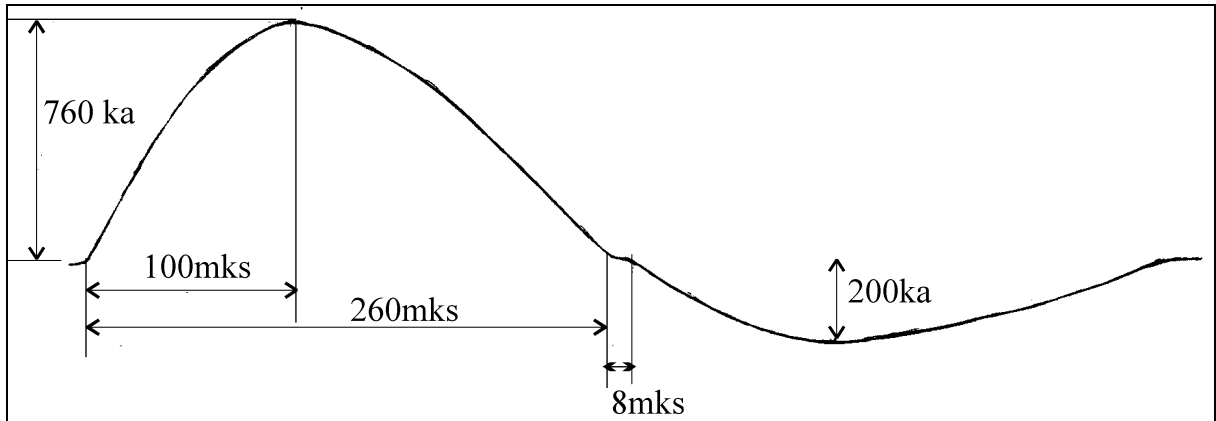
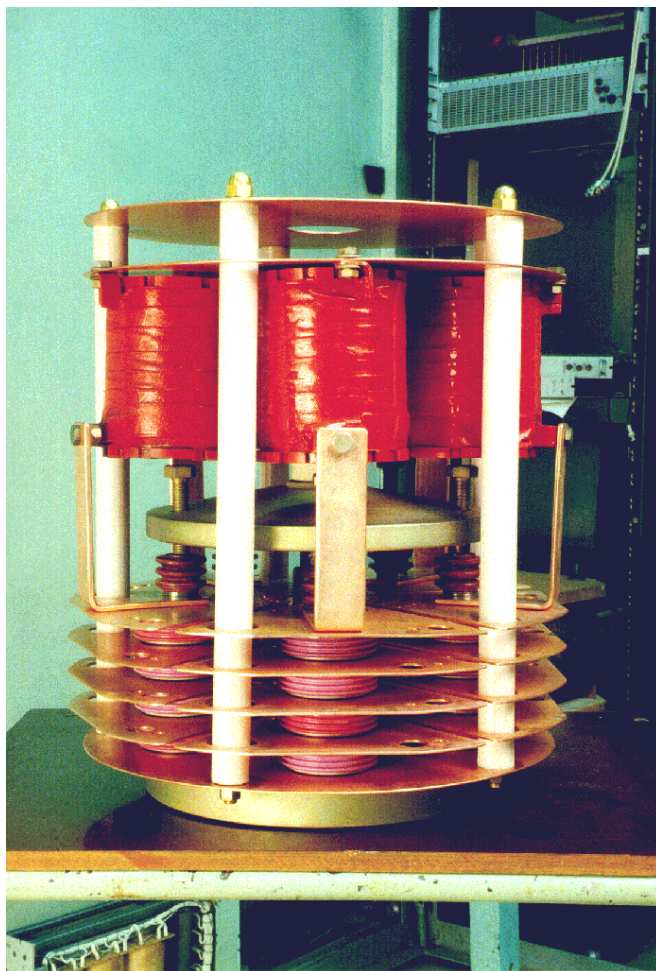**Fig. 7. Oscillogram of lens current**

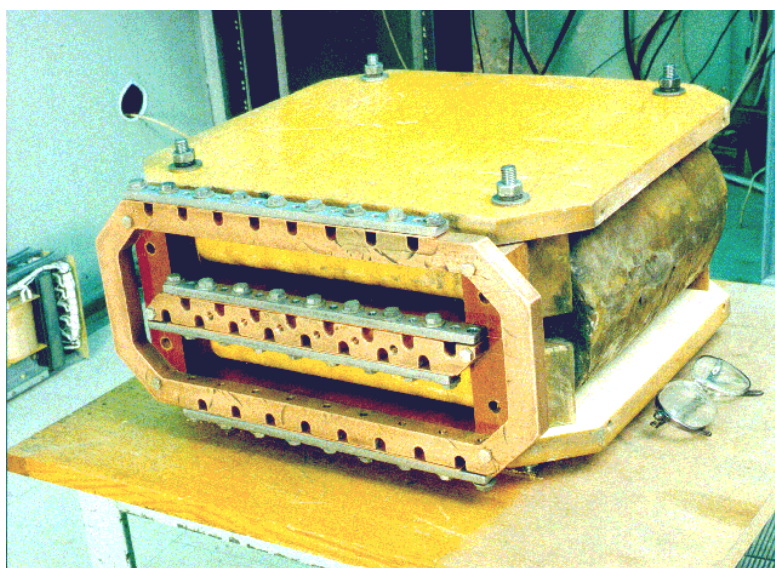# IX. Appendix (pictures)

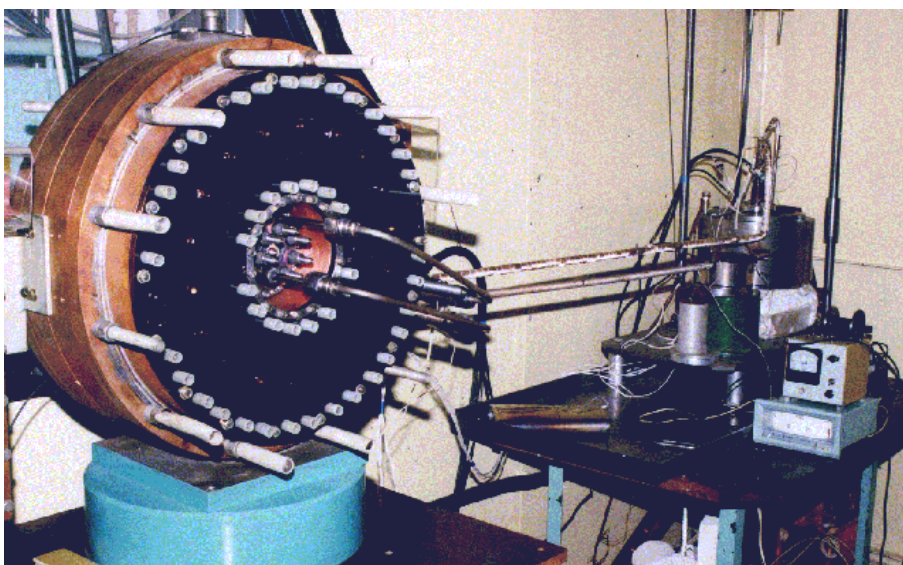**Fig. 8. Thyristor switch.**

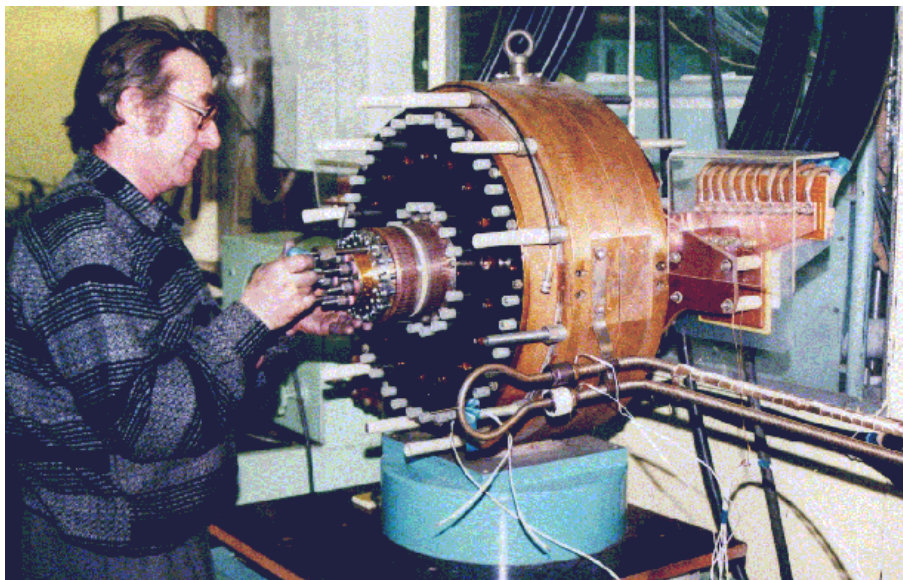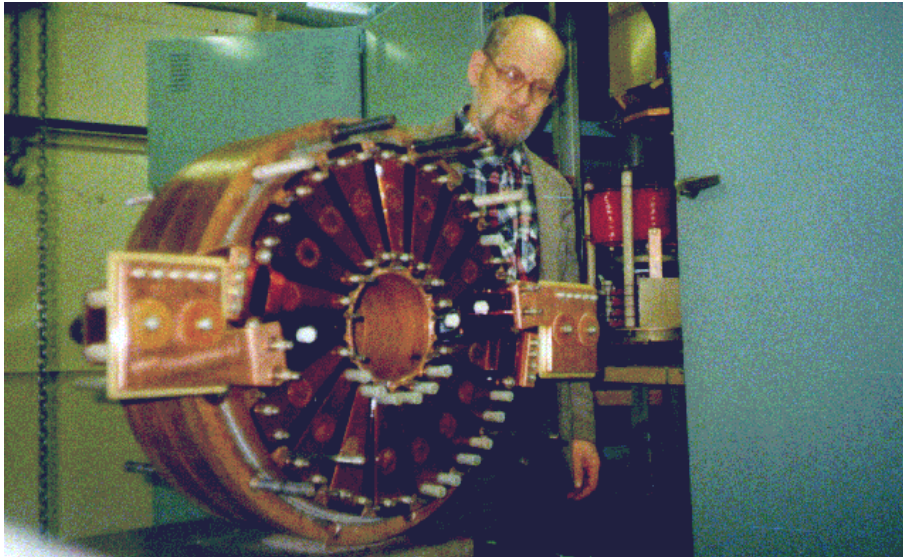**Fig. 9. Saturating choke**

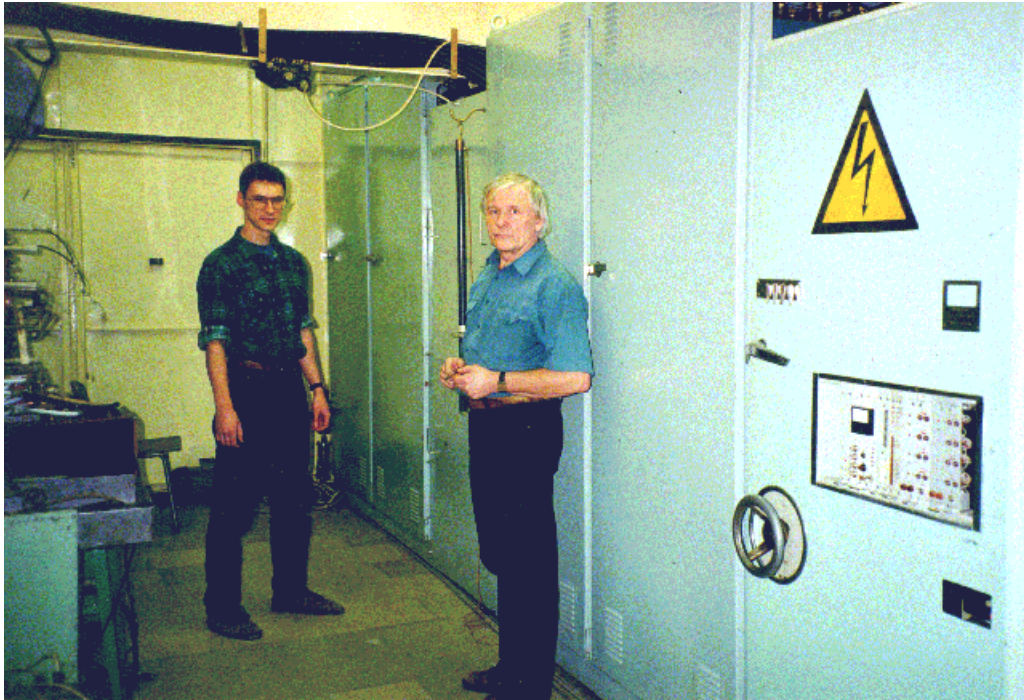**Fig. 10a,b,c. Matching pulse transformer**

Fig. 11a. Pulse Power Supply System
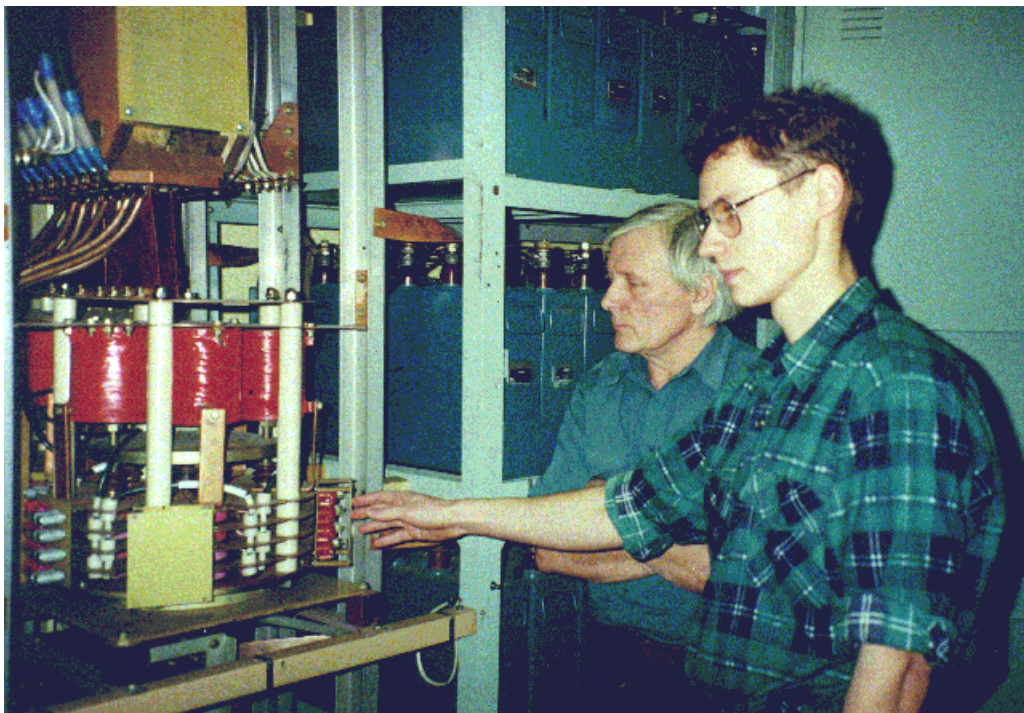

Fig. 11b. Thyristor switchs and capacitor bank of power supply system
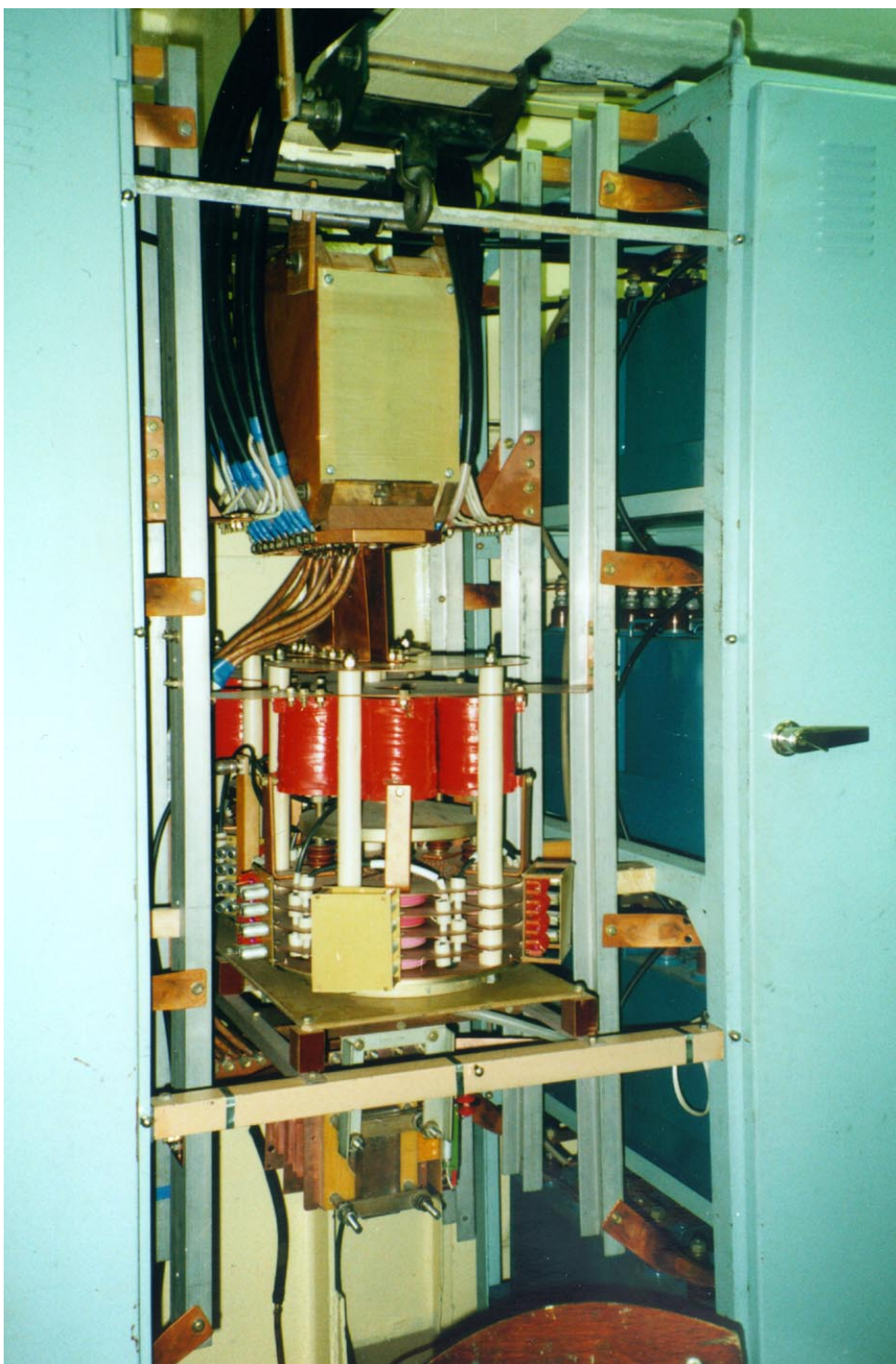
Fig. 11c. Fragment of pulse generator.

X.   References.

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Part B

Monitoring and control system of the «Lithium Lens» complex

Contents

In the project presented here there are two main objects of the monitoring and control:

- pulse power supply of the lens;
- lithium contour.

I. Monitoring and control of the lens power supply source

Monitoring and control of the lens power supply source (Fig.1) consists in the following:

1) voltage stabilization on the storage ring at the end of charge interval;

2) control of electric parameters of main components;

3) control and signaling the operation conditions such as air and water supply, conditions of the doors of electromechanical cabinets, etc;
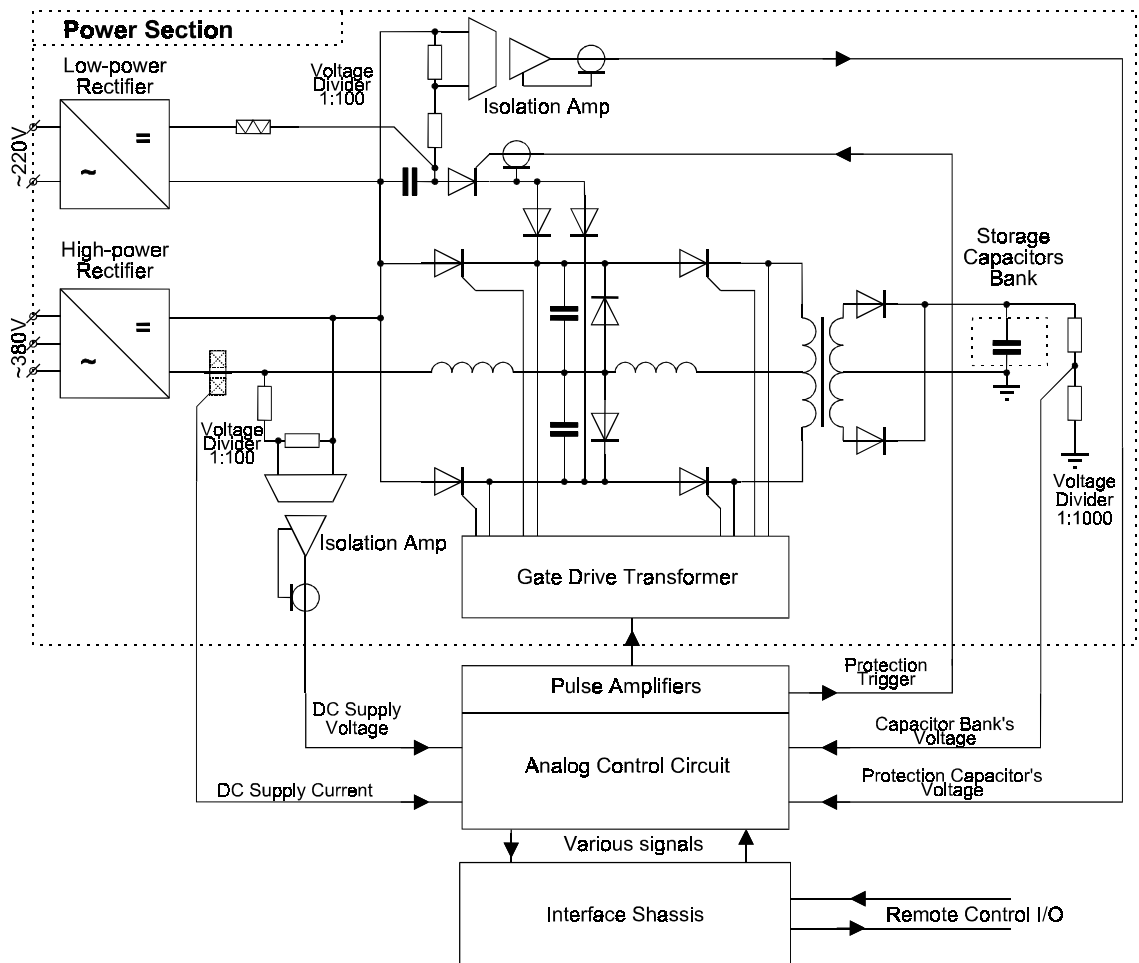
4) lens current stabilizing.

Fig. 1. Monitoring and control of the lens power supply source

1. Voltage stabilization at the storage ring

Fig 2 shows a simplified schematic diagram of U_0 correction with the change of rectifier voltage. The inverter is controlled by a two-phase voltage-to-frequency converter (VFC) whose pulse of each phase after amplification PA (*10 V, 10 A, 50 μs*) triggers an appropriate branches of inverter. Converter's frequency is linearly dependent of voltage U_{VFC} .
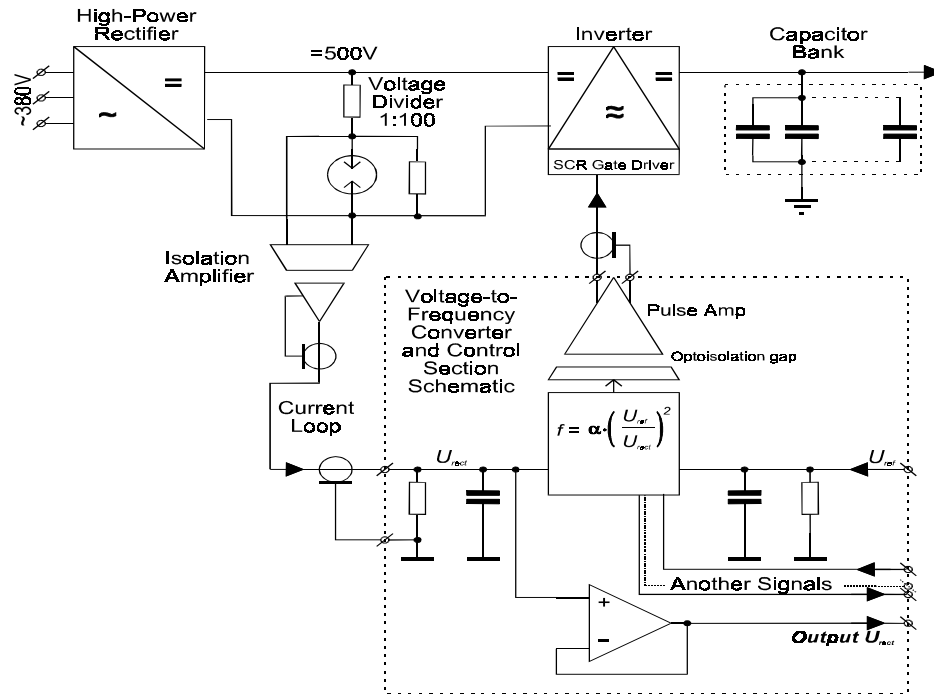
Fig. 2. Simplified schematic diagram of capacitor bank's voltage correction

For the time of charge τ at the inverter power supply voltage U_{rect} and inverter frequency f_i. The capacitance storage is charged up to the voltage value

$$U_{st} = 2U_{rect} \cdot \sqrt{f \cdot \tau \cdot \frac{C_0}{C_{st}}} ,$$

where C_0 is a dosing capacitance of inverter, C_{st} is the storage ring capacitance. Thus, in order to achieve the voltage of storage ring at the end of charge interval U_{st} to be always constant it is necessary to satisfy the following condition $U_{rect} \cdot \sqrt{f} = const$. This condition will be satisfied if the inverter control voltage

$$U_{VFC} = \alpha \cdot \left(\frac{U_{ref}}{U_{rect}} \right)^2 ,$$

U_{ref} is the reference voltage providing the inverter operation mode;
U_{rect} mains rectifier voltage;
α is a scale coefficient depending on the duration of the operation cycle.

Then the storage ring voltage at the end of the charge interval will be proportional to U_{ref}. Such a dependence enables one to keep in operation cycle a constant proportion between the duration of storage ring charge phases and the precise stabilization of voltage independently of the output voltage deviation of the mains rectifier.

The stabilization scheme is realized in the real time mode by means of two precise analog multipliers/dividers AD534 (Analog Device production) and it enables the stabilization of the storage ring voltage within the limits of 1%. A two-phase (voltage-frequency) converter is based on the microcircuit VFC32 (Burr-Brown production).

2. Apparatus protection system of charge device

For safe operation of the constant power charge device and for avoiding emergency of charge device, in the control system the analog apparatus control is envisaged in the real-time mode of the following parameters:

1. The mains rectifier voltage is U_{rect}. The minimum value $U_{rect.min}$ and maximum value $U_{rect.max}$ are given so to have a possibility of precise stabilization of the storage ring voltage within this interval and to avoid the hazard of malfunction of charge device components because of overvoltage. With the U_{rect} over the admissible limits the VFC and a triacs trigger's amplifier (PA) are blocked and the signal **«Overvoltage Rect.»** or **«Undervoltage Rect.»** is sent to the operator. With the return of U_{rect} into the interval of admissible values the system operation is renewed.

2. The mains rectifier current (I_{rect}). Maximum current voltage of rectifier $I_{rect.max}$ is given. Excess of this value means «overturn» of the inverter (simultaneous opening keys of both inverter branches). With the values I_{rect} over maximum values the triac controlled pulses are blocked and a fast protection system is triggered, the signal **«Overcurrent Rect.»** is sent to the operator.. The inverter's triacs are switched-off and rectifier current I_{rect} becomes zeroth, After this, the system will not renew the operation unless getting an explicit permission signal from the operator (**«Reset Protection»** signal).

3. The capacitance voltage in the system of the inverter protection electronic system is U_{pr}. The system of electronic protection operates safely only in the case if the capacitance C_{pr} (Fig.1) is charged up to the required voltage $U_{pr.min}$. Therefore, the triac control pulses should be blocked while $U_{pr}<U_{pr.min}$. In such a situation, the operator gets the signal **«Undervoltage C$_{pr}$»**. One has to note that C_{pr} has voltage up to *1 kV* with respect to the

inverter ground and U_{pr} is measured with the amplifier with galvanic isolation. Such an amplifier is based on the microcircuit AD202 of the Analog Device production and it has the transformer galvanic isolation at voltages of up to *2.5 kV*.

4. Voltage at the storage capacitance is U_{st}. Lens current will be defined by the voltage on the storage capacitor bank. Overvoltage of capacitor bank will bring about the overcurrent of lens, effect this will be a destruction of lens. Restriction of maximum voltage on capacitor bank prevents both a destruction of lens, and breakdown to insulation in capacitors. In order to avoid this the apparatus protection system blocks the inverter operation and in case of $U_{st} < U_{st.max}$ the operator gets the signal **«Overvoltage Storage Capacitance»**.

In addition to all said above, the charge device can be blocked by the signal **«Inhibit»** from CBS (Interlock Chassis) or by the signal from operator. Any operation of the protection system is induced on the control panel of operator by the light signal.

In the protection system the comparators of analog signals CMP04 of the Analog Device production and the basic logic microcircuits of 74LS series are used. For the control of all enumerated parameters the analog probes with current output are used for providing high safety protection of the circuit.

3. Device of blocks and signals (Interlock Chassis)

The constant power charge device is mounted in the electromechanical cabinet of the BINP standard. A simplified diagram of power supply is given in Fig.3.

The control of the operation conditions of the charge device and generator for lithium lens is performed by the following parameters:

1. Water pressure in the water cooling system (digital signal **«Water»**). In the absence of pressure the system operation is prohibited.
2. Air pressure in the air cooling system (digital signal **«Air»**). In the absence of air supply, the system operation is prohibited.
3. Control of temperatures of operational components of charge device (four analog signals **«T$_1$...T$_4$»**). At overheating of components the system operation is prohibited.

4. Condition of doors (digital signal **«Doors»**). Doors of the charge device abre blocked mechanically with MMB (Manual Mechanical Blocking). The system operation is prohibited if the only door is open.
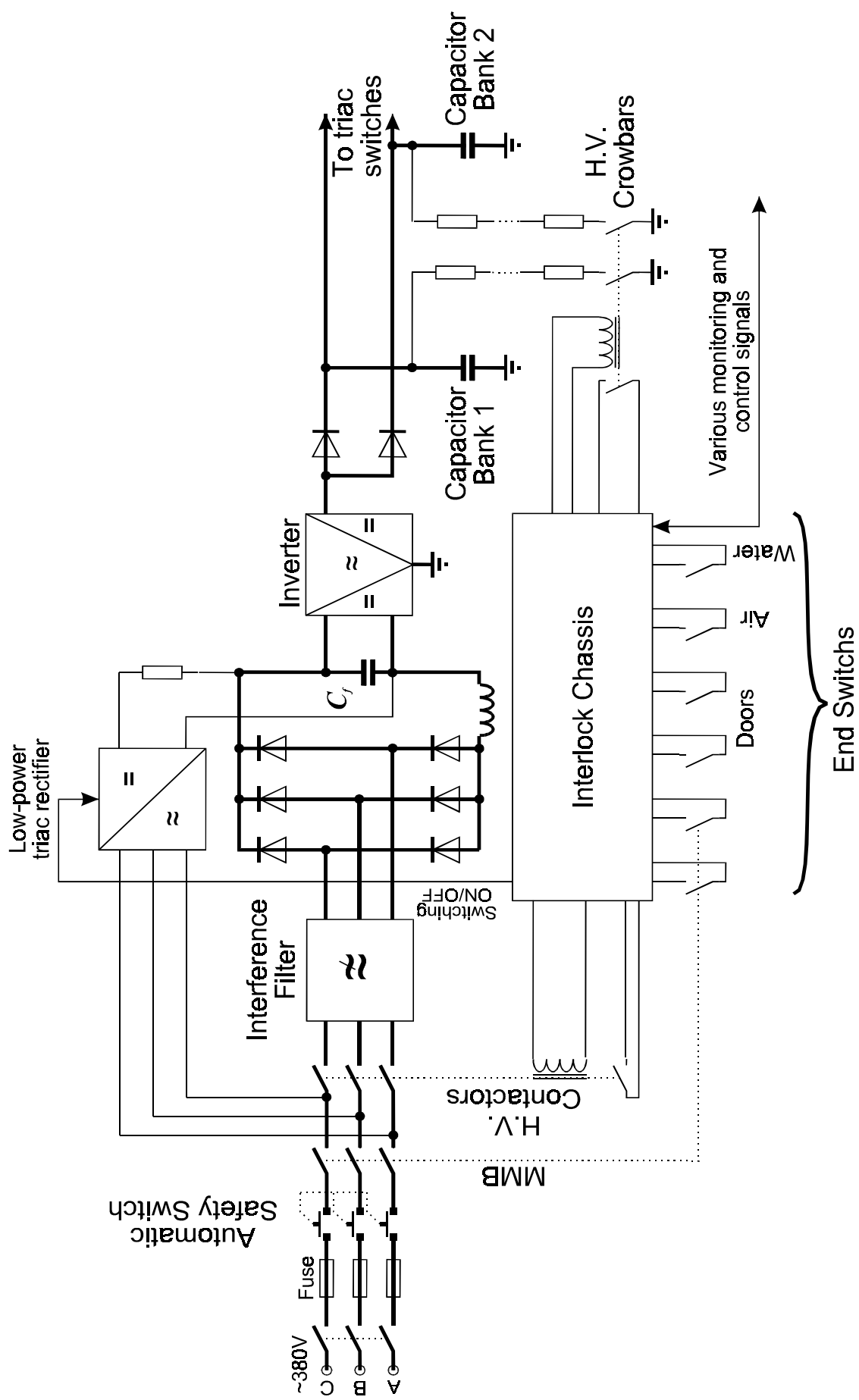
Fig.3. Simplified diagram of constant power charge

5. Condition of MMB. MMB has two ends contactacts: fully open (digital signal **«MMB open»**) and fully closed (digital signal **«MMB closed»**). In the condition of fully open, the LED indication is on allowing the operation of the personell with high voltage elements of the system, the autogrounders are blocked in the lower position, the contactors are blocked if they are not closed and the cabinet doors are de-blocked mechanically. In the fully closed condition, the cabinet doors are mechanically blocked and the closing contactors and elevation of autogrounders are allowed.

6. The condition of autogrounders (digital signal **«AG»**). Autogrounders block the storage capacitance via the ballast resistance to the «ground». Elevation of autogrounders is performed by applying voltage to the winding of the autogrounder winding by the command of the operator.

7. The condition of the High–Voltage Contactors (digital signal **«Power»**). Contactors provide applying 380 V onto the mains rectifier. They can only be triggered at elevated autocontactors. In order to avoid the charge of the filtering capacitor up to double mains voltage at the moment of energizing contactors a two-step switching of the mains voltage is envisaged: first, the low current rectifier charged the filtering capacitance up to the mains voltage; after 5…10 seconds the high current mechanical contactors are switching on. After successful operation of contactors, CBS applies the signal permitting the operation for the apparatus protection unit.

Collection of the binary states of the ends is performed with the optocouples; the control of the electromagnetic triggers and autogrounders is performed through the solid-state relay. This enables one to provide high reliability and antinoise protection of Interlock Chassis.

4. Control of the constant power charge device

The apparatus protection unit for the inverter and Interlock Chassis are linked by the two-directional fiber – optical channel to computer through the monitoring and control circuit described below in the report. The monitoring and control signals are given in Tables 1 – 4.

Table 1. Binary state signals given by protection system and Interlock Chassis.

№	Signal name	Signal description
1	"Power"	State of mains contactors
2	"AG"	State of autogrounders
3	"MMB Open"	MMB state
4	"MMB Close"	MMB state
5	"Doors"	State of doors
6	"Air"	Air cooling
7	"Water"	Water cooling
8	"Overvoltage Rect."	Mains voltage is higher than its admissible value
9	"Undervoltage Rect."	Mains voltage is lower than its admissible value
10	"Overcurrent Rect."	Ток выпрямителя выше допустимого
1	"Undervoltag Cpr"	Rectifier current is higher than its admissible value
12	"OSC"	Overvoltage Storage Capacitance

Table 2. Input analog voltages (12-bit accuracy).

№	Signal	Description
1.	U_{ref}	Reference voltage of VFC
2.	$U_{rect.min}$	Minimum admissible voltage for mains rectifier
3.	$U_{rect.max}$	Maximum admissible voltage for mains rectifier
4.	$I_{rect.max}$	Maximum current of mains rectifier
5.	$U_{pr.min}$	Minimum voltage in the fast protection system's capacitance.
6.	$U_{st.max}$	Maximum admissible voltage on capacitive storage

Table 3. Output analog voltages (12-bit accuracy).

№	Signal	Description
1.	U_{rect}	Voltage of mains rectifier
2.	I_{rect}	Mains rectifier current
3.	U_{pr}	Capacitance voltage in the electronic protection
4.	U_{st}	Storage capacitance voltage
5.	T_1	Temperature of charge device components
6.	T_2	
7.	T_3	
8.	T_4	

Table 4. Binary signals controlling the charge device

№	Signal	Description
1	"Switch Power Output"	Switching the thyristor control pulses
2	"Inhibit"	Permission of VFC operation
3	"Reset Protection"	Reset of rectifier current protection flip-flop
4	"AG Up"	Elevation of grounders
5	"High Power On"	Switching mains High–Voltage Contactors

Reference voltages for the apparatus protection unit is given by operator through a multichannel DAC. A multichannel DAC measures the controlled inverter parameters which are further transmitted into computer and displayed on the screen. In addition, with the help of DAC the temperatures of charge device components are measured. The data obtained are processed by computer and on this basis the operation of charge device is controlled.

5. Lens current stabilization

Let us define factors affecting the value of lens pulse current. At first approximation, the lens current amplitude is determined by the following expression:

$$i(t) = \frac{U_0}{L \cdot \omega} \cdot e^{-\frac{R}{2L}t} \sin(\omega \cdot t) ,$$

where R is a circuit active resistance, U_0 is a storage initial voltage, L is lense inductance. It is seen that the main contribution into instability of I is given by an instability U_0. Parameters R and $L \cdot \omega$ can change slowly during the lens operation because of its temperature change which influence also on the lens current stability.

For the compensation of all the factors given above and lens current stabilization it is used the lens current shape pulse detector described below. The current amplitude value measured with the detector is processed with computer and on the basis of the data obtained the reference voltage controlling the charge device inverter frequency is corrected. Thus, the current is stabilized from pulse to pulse.

II.   Lithium contour

Schematic diagram of the lithium contour is shown in Fig.4. The schematic shows the probes and executing devices of the control system including the following:

- temperature probes (thermocouples) homogeneously distributed along the lithium contour,
- probe of lithium static pressure,
- lithium flow probe (consumption meter),
- current probe of electromagnetic pump,
- probe of lens pulse current,
- unit supporting the lithium static pressure with electromechanical drive,
- a set of electric heaters distributed along the lithium contour ,
- electromagnetic regulator of heat exchanger of cooling contour,
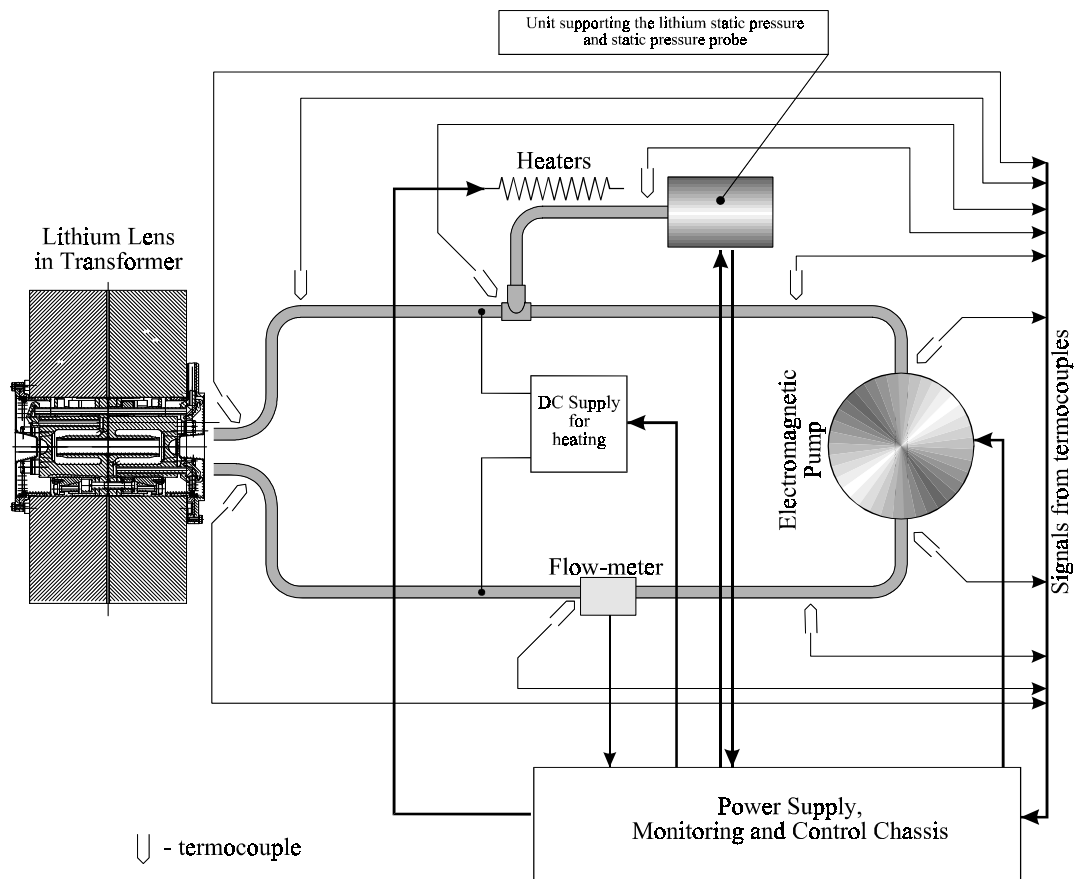- lens power supply.

Fig. 4. Schematic diagram of the lithium contour

The operation scenario of the monitoring and control unit for lithium contour has two distinguished stages - the preparatory and operation stages.

The purpose of the preparatory stage is to provide the operational state of the contour. To this end, it is necessary :

- to heat all the components up to the temperature exceeding the lithium melting temperature;
- to set the initial static pressure in the contour on the level of *50 atm*;
- provide the given value of circulating lithium flow by indications of consumption meter and with the help of electromagnetic pump;
- upon equalizing temperatures of all the components to shift to the mode of its stabilization with the help of heaters and regulator of cooling contour and after that, to achieve the lithium pressure value of *300 atm*.

One should note that at the preparatory stage, for heating lithium in the lens its power supply source is used which is operated in the mode with low amplitude of current pulses at higher frequency of cycles.

In the operation mode corresponding to the standard value of pulse current of the lens power supply source load with the pulse repetition frequency *0.5...1 Hz*. The heat release in the lens exceeds the level required for keeping the lithium temperature in the whole contour on the given level (*200...220°C*). An excessive energy is removed into the cooling contour through the heat exchanger. The flow of cooling liquid (water) is regulated by the electromagnetic regulator.

For the realization of the lithium contour operation scenario the following components are included into the monitoring and control system (Fig.5):

- integrating ADC with a 16-channels input multiplexer operated in the mode of the cycle inquiries of the current values of signals from the thermocouples, lithium flow probe, static pressure probe, and the current probe of electromagnetic pump.
- A 16-channels control input/output register used for fixing the current states (switched on/off) of executing components.
- A two-channel DAC used for the control of the phase-pulse regulator of the power supply of electromagnetic pump and the drive of cooling contour valve.

In addition to all the devices mentioned above the monitoring and control system of lithium contour includes the meter of the shape of single pulse signals designed for fixing the shape of lens current.
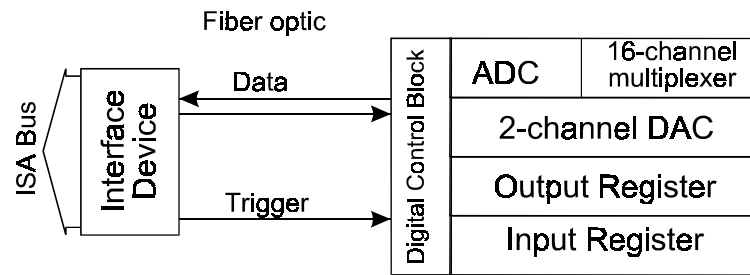

Fig. 5. Monitoring and control system the lithium contour operation

1. Heating And Temperature Stabilization System Of Lithium Lens

The schematic diagram of the system is given in Fig.6. Heaters made of highohmic wire with insulating shell wound on the lithium line components as well as on the adjacent components of the line having the lower resistance were used as heating sources for lithium at the initial stage of system operation.

With the triac switches operated under the control of output register the wire heater are power supplied directly from the alternate current mains with voltage of 220 V.
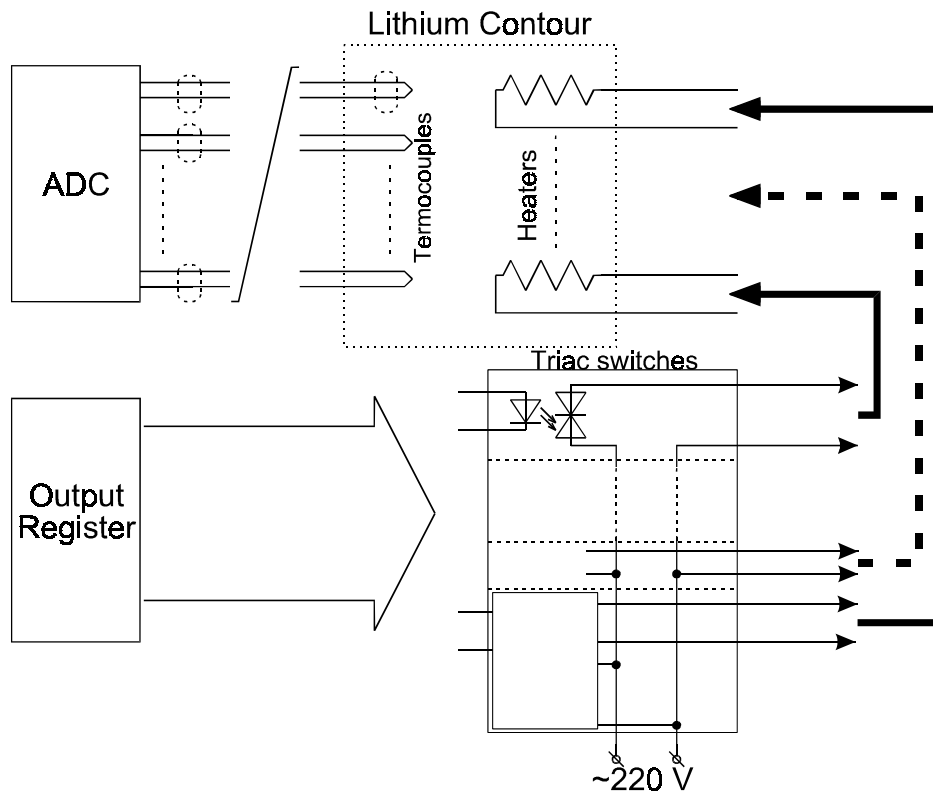
Fig. 6. Heating and temperature stabilization system of lithium lens

The connecting pipes of lithium line are heated by applying current to them. The current sources are the mains step-down transformers with triac switches in the primary winding. The output register switches on/off these switches and consequently currents flowing along the lithium contour elements.

An electric power of each heaters lies within the range from 0.3 to 1 kW. The current protection of heater power supply circuit is performed with the current relay of the mains breaker.

The lithium temperature distribution in the contour is controlled with the help of thermocouples by the ADC.

The operation of the system at the stage of heating contour looks as follows:

- with the output register and triac switches all heaters are switched on, electromagnetic regulator of cooling contour is closed and lens power supply is shifted to the operation mode with low amplitude current value;

- the lithium temperature distribution along the contour is controlled with thermocouples and ADC;

- upon reaching an ultimate temperature value at any local point of lithium contour the heater connected with the point is switched off;

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- the presented process of discrete control by switching on/off heaters proceeds unless equalizing temperatures at all the controlled points at a given level (*200...220°C*).

In the operation mode, the main heat releasing components of the lithium contour became the lithium lens itself and electromagnetic pump. Thermal loss in these components exceed the level required for keeping lithium in a liquid state.

Therefore, with the lens operation in this mode the heaters are switched off and lithium temperature is stabilized on the given level with the control of cooling liquid flow in the heat exchanger. The control of water flow is performed by an electromagnetic regulator of cooling contour. Its position changes the crossection of inlet pipe conduit and therefore, the heat exchanger efficiency. The current source control is performed by the phase-pulse regulator in the secondary circuit of step-down transformer. In this case, the source current value is directly dependent of the reference current value formed by DAC.

Thus, the lithium temperature stabilization contour in the operation mode comprises:

- measurement unit consisting of thermocouples and ADC;
- executing device consisting of DAC, controlled current source and electromagnetic regulator;
- decision taking unit based on some controller forming a signal adequate to the current situation.

2. Unit for keeping lithium static pressure

Keeping the lithium static pressure in a lens and its contour is performed with the help of pressure probe and an executing device which consists of a dc current reversible motor, a high deceleration factor reducer converting the rotary motion of motor rotor into an advance motion, and hydrocylinder (Fig.7)
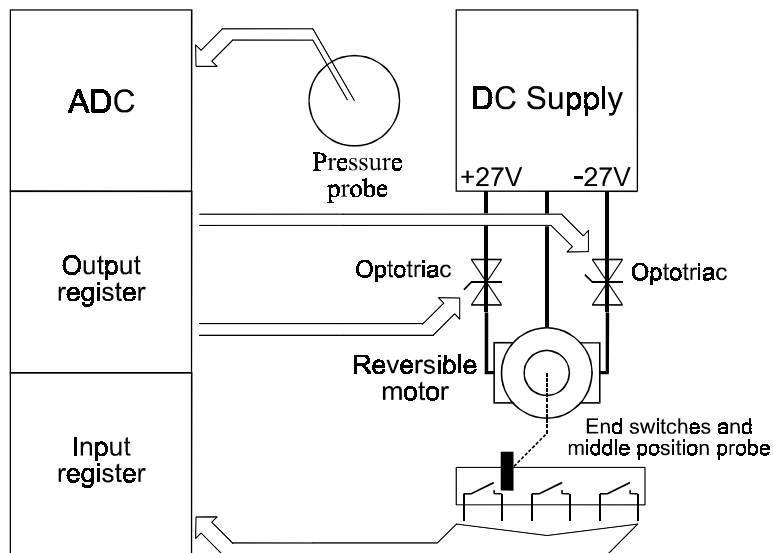
Fig. 7. Unit for keeping lithium static pressure

The operation of the lithium static pressure control system starts after heating the lithium contour prior to switching on the electromagnetic pump. Because of the fact that lithium has a large coefficient of volume expansion the local pressures at various sections of contour will be changed during heating and transition through the melting point. In order to avoid additional load of lithium contour its initial pressure should be reduced down to the level near of *50 atm* and kept its value unless obtaining the lithium circulating flow in the system.

During the shift to the standard operation mode the pressure in the system increases up to value near of *300 atm* in order to eliminate the possibility of lithium break away from walls by magnetic field of lens current.

Operation of the contour for regulating the lithium static pressure is quite simple. The current pressure in the contour is converted by the pressure probe into an electric signal whose value is measured by the ADC. The pressure change is performed by the executing device motor. The motor rotation direction is directly related with the direction of pressure change in the system and the value of this change depends on the hydrocylinder motion and consequently on the duration of motor switching interval.

On the basis of the current value of static pressure in the system and its required value the controller with the help of output register selects the motion direction of the executing device motor and the duration of its switching interval. The resulting pressure in the system is controlled by ADC. If necessary to change substantially the pressure in the system, the process of its realignment is performed by the succession of iterations.

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In the executing device of the pressure stabilization system a dc current motor with an operation voltage of 27 V is used. The step-down transformer with a rectifier in the secondary winding is used as a power supply source. The power voltage of required polarity is applied to the motor through triac switches operated under the control of output register.

The upper and lower utmost points of hydrocylider position are connected to end switches limiting the range of its motion. In the executing device, in addition to the end switches there is also a contact probe of the middle position of hydrocylider. The states of all switches and the middle position probe is checked through the input register by the controller during executing all the operation relater to the change of lithium static pressure in the system.

3. Monitoring and control system for electromagnetic pump operation

The lithium circulation in a lens and lithium contour is provided by the electromagnetic pump whose efficiency depends on the current value of the power supply (Fig.8). The current of a source designed by the classic scheme with a step-down three-phase transformer and phase pulse circuit of proportional control in the transformer secondary circuit depends linearly on the reference voltage value formed by the DAC. The mean value of the lithium flow rate in the contour with the given cross section is converted by the flow probe into an electric signal measured by ADC.

The operation principle of the lithium flow control in a lens is quite clear. According to the given value of flow rate and its current value measured by ADC the controller forms the control code for the DAC and the power supply current of electromagnetic pump.

The process of alignment of the flow rate is performed in a cyclic way thus enabling one to keep the lithium flow within the given limits independently of the temperature fluctuations.

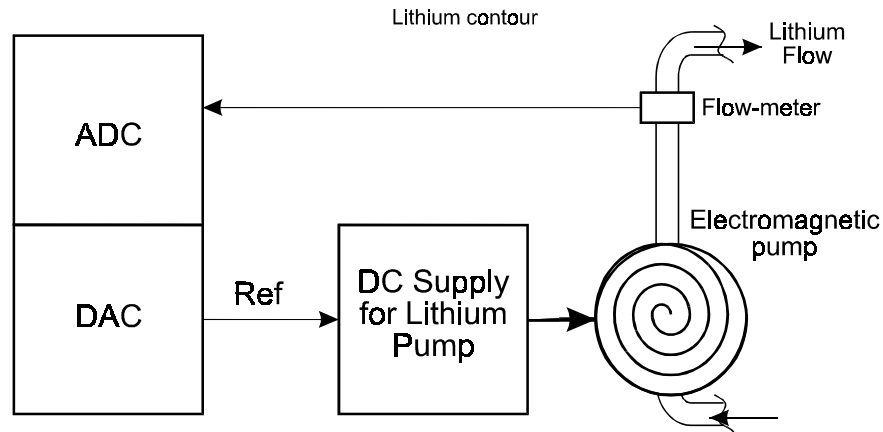The electromagnetic pump current control circuit has the built-in means of current control and hazard protection.

Fig. 8. Monitoring and control system for electromagnetic pump operation

The pump current value controlled by an appropriate probe is measured periodically by the ADC. The ADC measurement results are compared by controller with the given threshold values of a current. If the measured current values becomes beyond the threshold values both the power supply sources of electromagnetic pump and lens are switched off. Similar actions are undertaken if the lithium pressure value in the contour drops lower than the given value.

4. Indicator of lens current pulse shape

The lens current behavior dynamics provides both the quantitative and qualitative data enabling one to estimate the operation character both for the lens and for the states of the lithium contour and power supply source. In particular, during the transition through the lithium melting point in the operating section of the lens its active resistance of lithium changes by several times thereby causing changes in the current pulse shape. Because of high informaticity of such a diagnostic a special channel for the lens current shape measurement was involved into the monitoring and control system of the lithium contour (Fig.9). Rogovsky coil whose output signal through integrating RC-circuit is applied to the input of the indicator of shapes of individual pulse signals is used as current probe of the given channel. The recorder is based on a 12-bit ADC with a discretization frequency of 20 MHz and it is equipped with a buffer memory device at 32K words.

During the operation of recorder the record of signals formed by ADC into the buffer memory device starts from the moment of applying an outer triggering pulse related to moment of formation of the next current pulse by the lens power supply source. The data storage process

continues up to filling in the entire volume of the memory device. Further, the stored data array is read through link by computer, processed and displayed on the monitor in the form of oscilloscope trace.
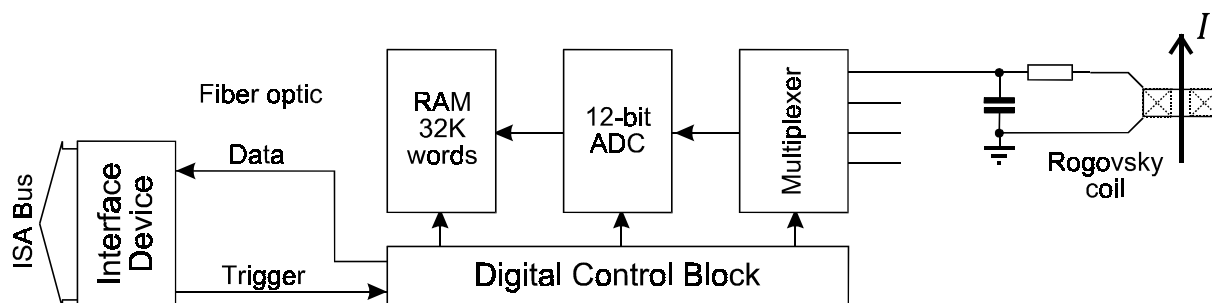

Fig. 9. Indicator of lens current pulse shape

The feature of the construction of the channel for recording the lens current pulse shape is that the used record module is galvanic isolated from the computer with the fiber optic communication link. This enabled us to locate the recorder near the probe and to decrease the length of signal lines and thereby to decrease substantially the influence of electromagnetic noises on the measured signal.

5. Design and construction of components of monitoring and control system of lithium lens

The monitoring and control system of lithium contour comprises three basic construction elements: -commercially available modular computer MIC2000 of Advantech production, a monitoring and control unit, and the current shape recorder module.

Additionally to the standard peripheral equipment (monitor, keyboard, disk, etc) the computer is equipped by two interface circuits providing a two-directional exchange by data and control commands along the fiber optic communication links between the processor's ISA bus, the monitoring and control unit and the module of lens current shape recorder. The interface circuits are based on the programmable logic matrices of FLEX10K series of Altera production that enables the realization of any standard protocol of exchange with external devices along the communication links as, for example, CAN, MIL-STD-1553B or any other most relevant to the task under solution.

In our case, the use of sequential fiber optic communication links in the control system enables one to eliminate the galvanic connection of the computer with the power supply equipment which, of course, decreases the reliability of the whole system operation.

The control unit embedded to BINP standard cabinet «CHERRY». This cabinet also comprises all the basic power supply components (power supply sources of the electromagnetic pump, electromagnetic regulator of cooling contour, motor for the lithium pressure stabilization system, step-down transformers and thiak switches for the lithium contour heating system, mains breakers, and blocking relays).

The monitoring and control unit comprises a 16-bit 16-channel ADC of integrating type, an 8-channel 16-bit DAC, 16-bit input/output control register as well as the built-in controller and an interface to the sequential fiber optic communication links.

The ADC is galvanic isolated from other components of the monitoring and control unit and it has an individual power supply source with the transformer isolation. The maximum admissible voltage of ADC isolation from other components of the unit is *1000 V*. ADC inputs are differential providing the high level of noise attenuation. The suppression of the mains noises is achieved by the classic procedure of «relation» of the duration of integration period of the input signal to the mains period.

Maximum voltage of ADC intrachannel isolation is *70 V*.

The measurement range is selected programmably and it is changed within the interval from *50 mV* up to *5 V* through the whole scale.

The DAC of the circuit are based on the commercially available DAC AD420 of Analog Devices production. The source of output current of these ADC enable the operation at an ultimate accuracy within the range *0...20 mA* providing the suppression of noises with an amplitude of up to *30 V*. Because of this, the direct galvanic connection of the DAC output cascade is possible by the scheme of «current loop» with the object of control with no loss of accuracy in the reference signal transfer channel.

The input/output control register of the circuit are galvanic isolated from the objects of monitoring and control.

The drivers based on the solid stay relay are used as the output cascades of the control register. They allow the commutation of both the alternate and direct voltages with an amplitude of up to *60 V* at the load current of up to *1 A* and they have an ultimately admissible voltage of isolation of *1500 V*.

The inputs of the control register are designed for the input current range *0...10 mA* and have the isolation voltage of up to *1000 V*.

The controller and interface of the monitoring and control unit are based on the programmable logic matrix of 10K series of Altera production. Depending on the circuit design it enables one to realize either the completely autonomous algorithm for the control of all the components or the algorithm depending on the computer commands coming along the serial communication link.

In our case, the controller being operated autonomously provides the cyclic inquiry of all the ADC channels, compares the obtained current signals with the reference signals loaded by communication links from the computer and forms all the governing actions. It checks also with the help of the control register the current state of executing elements of lithium contour and if necessary, provides the hazard de-energizing of the system. Information on the current state of executing elements as well as the results of ADC measurements through all the channels are periodically transmitted by the controller to the computer along the communication link for its further display on the monitor screen.

The module of the lens current shape record (Fig.10) is made as local device combined with the current probe.

The module main components are: a 4-channel multiplexer of input signals, a high sped 12-bit ADC, the buffer memory devices at 32 K words, the control circuit and interface for the serial fiber optic communication link.

The recorder operation cycle starts from applying the trigger pulse to its control circuit along one of the communication links. From the very moment, ADC shifts to the mode of measurements of current values of the input signal amplitude applied to its input through the multiplexer. The ADC discretization frequency is fixed and it is equal to 20 MHz. The succession of ADC readings is recorded into the buffer memory device unless the complete filling its volume. Further, the stored data array is transmitted along the communication link into the interface module connected to ISA bus of the computer. Upon the reading and processing the array is displayed on monitor in the form of the oscilloscope trace.

The main feature of the recorder described is that it is galvanic connected only with the current probe. Its power supply source is based on the converter with isolating transformer having low value of the transfer capacitance and all the remained communication links are fiber optic links. Because of this fact, as well as due to specific location of the recorder in the shielded body, we

managed to reduce substantially the affect of external electromagnetic noises on the measuring line and to achieve an ultimate accuracy of the used ADC.

III. Software for monitoring and control system of "lithium lens" complex

The commercially available modular computer MIC-2000 connected with specific interfaces to all the measurement and control equipment is planned to be used for the control of a system. It is assumed that the computer will be operated under Windows-95. The use of this operational system will enable one by the only computer to control two objects weakly connected from the viewpoint of control problems: pulse power supply sources of lens and lithium contour. Each object will be controlled by separate process (task) and the synchronization of these processes will be performed with the help of standard means of Windows-95.

1. Software for the lens pulse power supply source

The operation with the pulse power supply source can be divided by two basic stages: parameter alignment stage and the stage of operation cycle.

Fig.11 shows the prototype of the operator interface designed for the control of the pulse power supply source of the lithium lens in the mode of parameter alignment.

During the alignment the operator gives the required parameters for all the units of the power supply source. In this case, the software controls the introduced values and does not allow them to violate the given limits. For the operator convenience the possibility of the storage and further load of the current operation modes as well as the restoration of initial values of parameter given by the source designers is envisaged.

The operator can give new values of the following parameters:

- minimum and maximum voltage of rectifier U_{rect};
- minimum voltage on protection capacitor $U_{cprotec}$;
- maximum voltage on storage bank U_{char} ;
- maximum current consumed from rectifier I_{rect};
- maximum operation frequency of inverter components (up to 4th channels);
- Capacitance of the storage bank C_{store};
- Electric parameters of discharge contour (R and L).

At the end of alignment the processes is shifted into the operational regime. Prior to switching on the source to the load (lens) all the blocking and signals at the control points are checked. In the process of operation of the source the check of signals at the control points is performed periodically. Upon reaching the limits by current values the operator monitor displays an appropriate signal. In case of exceeding critical values by the signals the source is de-energized.

During the operation of the source control system the lithium lens current oscilloscope traces and storage voltage are displayed on the screen and the current values of the controlled parameters of the source are displayed in the form of digits and histograms.

Fig.12 shows the operator interface prototype for the control of the pulse power supply source for the lithium lens in the operation cycle mode.

2. Software of lithium contour

Heating of lithium contour and its shift into the operation regime is performed by heater controlled by the process responsible for the lithium contour. The same process solves also the control problems for lithium flow through the lens with the help of electromagnetic pump and consumption meter as well the stabilization of lithium static pressure in the system.

Prior to the operation beginning the operator has a possibility to define the required values of lithium temperature, pressure in the contour and lithium flow through the lens. The variation of these parameters is possible only within the limits given by the designers of the system.

As an example, Fig.13 shows the operator panel prototype for the process of lithium temperature control in the mode of parameter alignment.

3. Mutual relation of processes

Synchronization of control processes by the lithium contour and lens power supply source is provided with the help of exchange by the messages. The messages contain information on the current state of the equipment in subsystems and a commands provided the interaction of control processes. The exchange procedure is realized with the help of the standard means provided by the operational system Windows-95.

As already mentioned above, all the processes are performed within the frame of one commercially available computer which actually is the console of the lithium lens operator. In order

to get an access to information on the equipment state and current operational state from other places it is envisaged to introduce it into the local network with the help of the interface Ethernet. An exchange with external programs is performed according to TCP/IP protocol. In this case, the lithium lens control is only possible from the operator console and other computers can be used as auxiliary monitors.

The lithium lens is a complete system to be operated in the experimental facility. However, at present, we have no information on the connecting interface and exchange protocol required for including the lithium lens into the complex. For the solution of the given problem an additional discussion with the customer is required.

4. Prototype software

In order to provide the alignment of the lithium lens in the period necessary for the production of equipment and software the required set of measuring and control equipment was compiled from the CAMAC modules with satisfactory parameters. For the control of these modules was written work program providing the control of the lithium contour heaters and lithium temperature control at 16 points. Fig.14 shows the operator panel of the program.
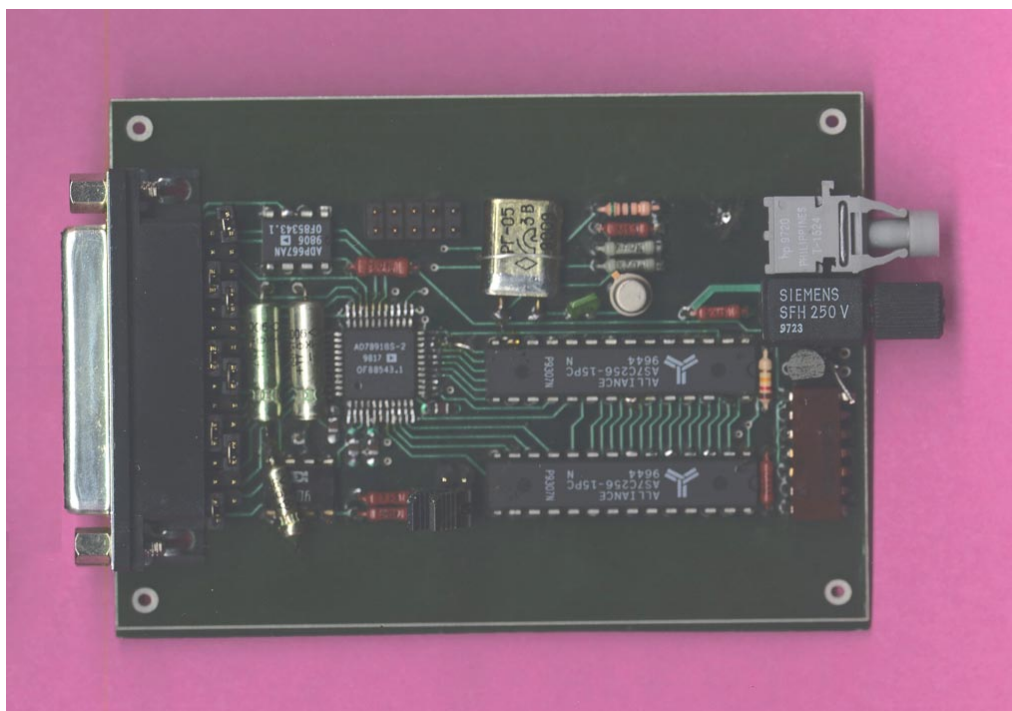
IV.   Appendex (Photo)

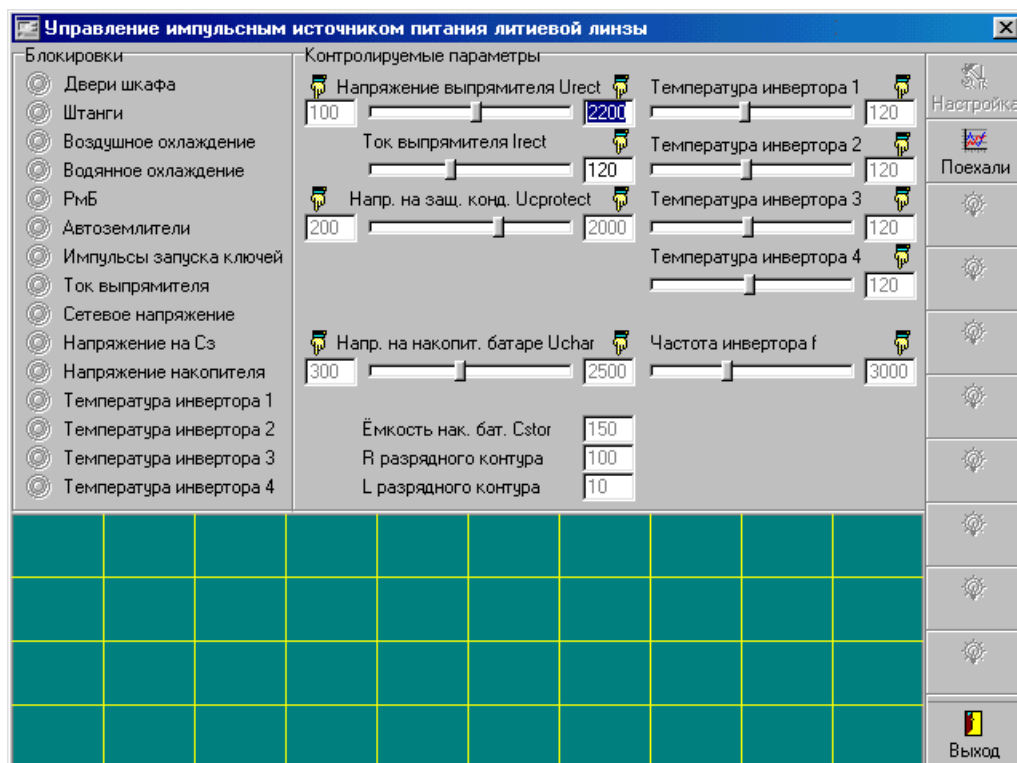**Fig. 10. The module of the lens current shape record**

Fig. 11. Prototype of the operator interface for the control of the pulse power supply source in the mode of parameter alignment
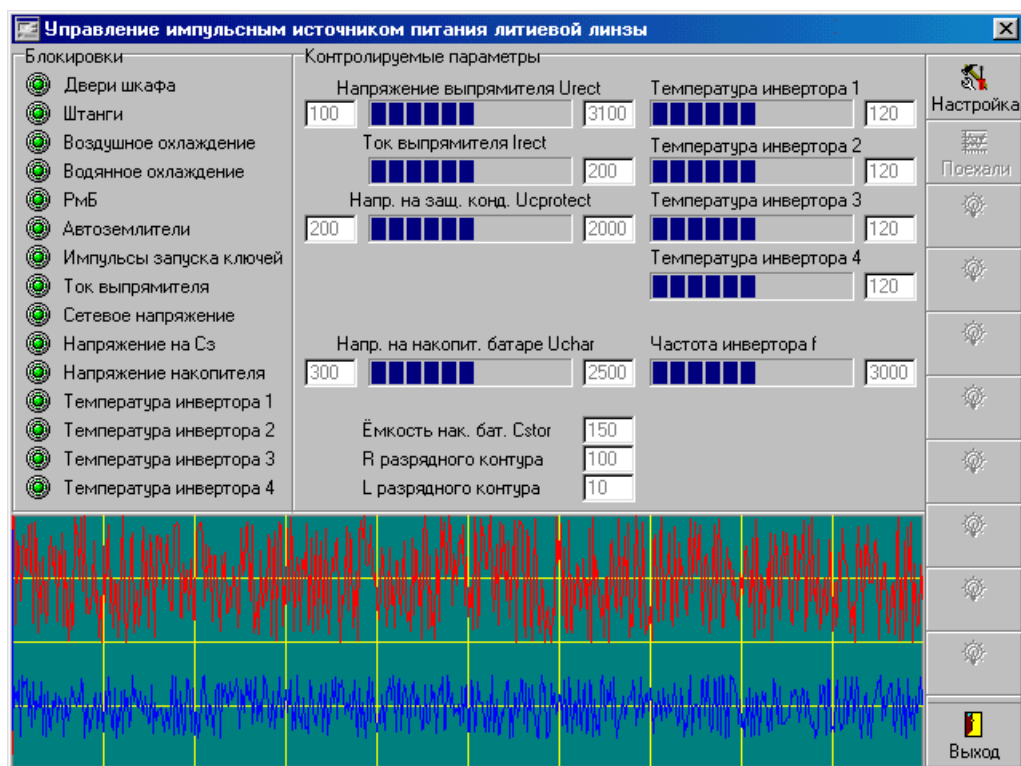
Fig. 12. Operator interface prototype for the control of the pulse power supply source for the lithium lens in the operation cycle mode.
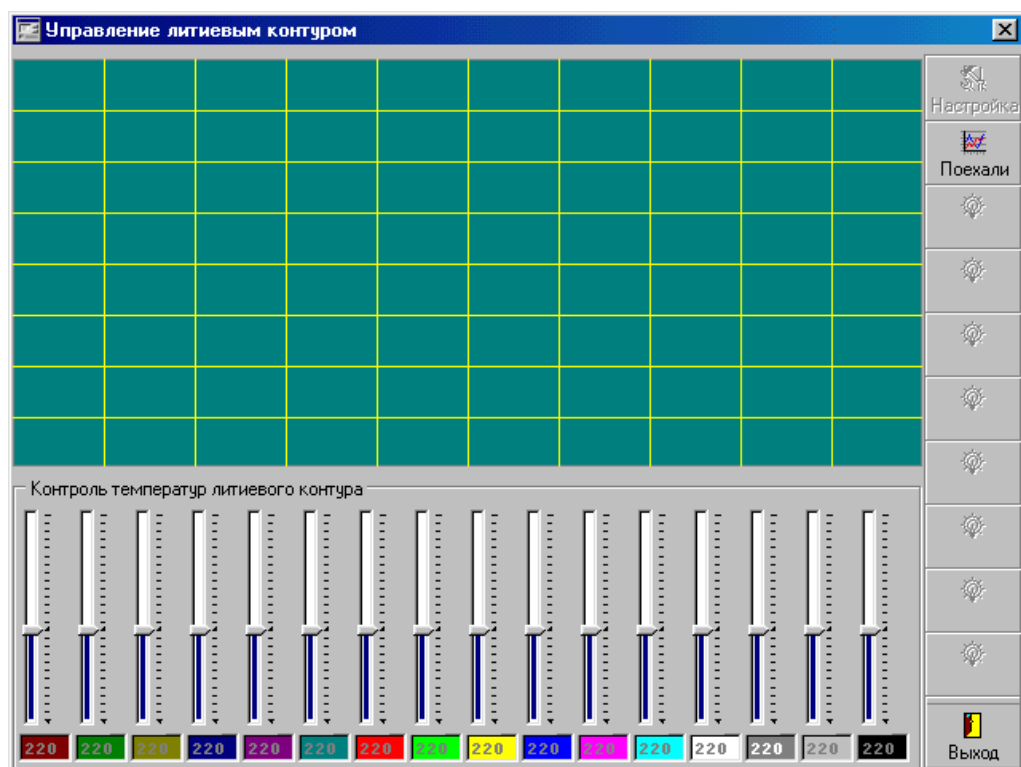

Fig. 13. The operator panel prototype for the process of lithium temperature control
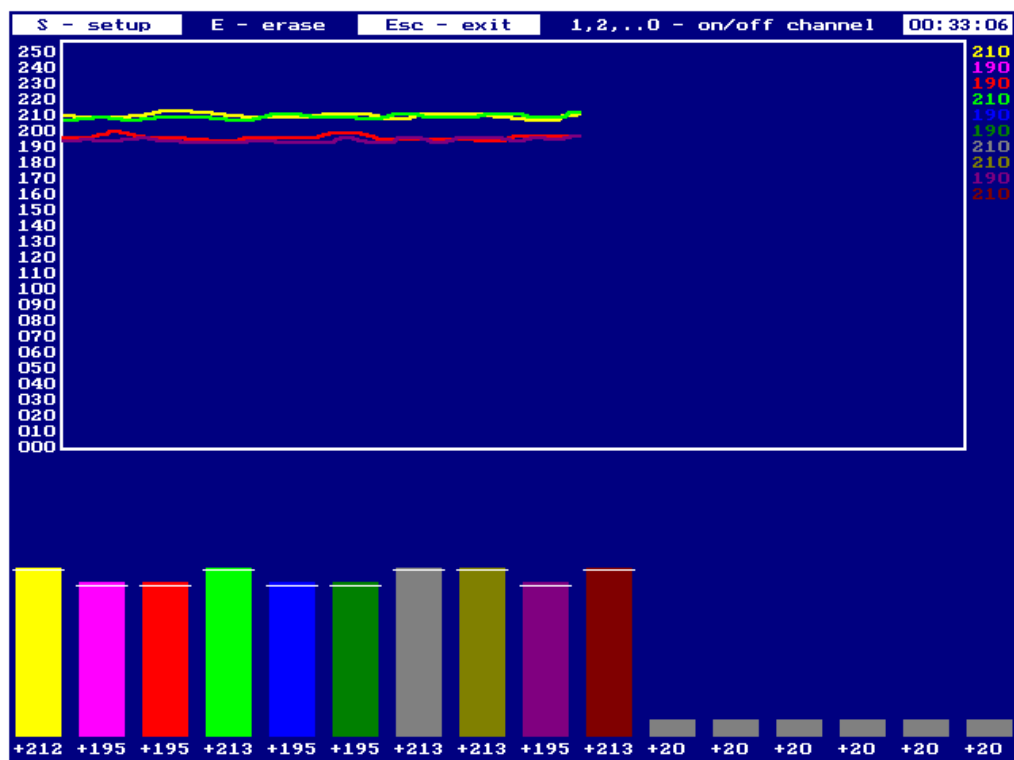
Fig. 14. Operator panel of the program for control of the lithium contour heaters and lithium temperature measurements.